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DRAFT IEP MAST REPORT

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Interagency Ecological Program (IEP) Management, Analysis, and Synthesis Team (MAST)

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- The process and the timeline for developing, reviewing, and completing this report is described in a companion document available at www.water.ca.gov/iep
- Approval of the final version of this report is expected in December 2013.
- Some content and graphics, including the executive summary and some of the conclusions, remain under development and are not included in this draft report.
- Technical editing of all information in this draft report, including grammatical and style changes and inclusion of additional citations and references will be ongoing.

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37 **Interagency Ecological Program, Management, Analysis, and Synthesis Team**

38 **An updated conceptual model for delta smelt: our**
39 **evolving understanding of an estuarine fish**

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Abbreviations

101	CCF	Clifton Court Forebay
102	CM	conceptual model
103	CVP	Central Valley Project
104	Delta	Sacramento-San Joaquin River Delta
105	DRERIP	Delta Regional Ecosystem Restoration Implementation Program
106	DSC	Delta Stewardship Council

107	EMP	Environmental Monitoring Program
108	ERP	Ecosystem Restoration Program
109	FLaSH	Fall Low Salinity Habitat
110	FMWT	Fall Midwater Trawl Survey
111	IEP	Interagency Ecological Program
112	LSZ	low salinity zone
113	MAST	Management, Analysis, and Synthesis Team
114	NRC	National Research Council
115	OMR	Old and Middle River
116	POD	Pelagic organism decline
117	SFE	San Francisco Estuary
118	SKT	Spring Kodiak Trawl Survey
119	SL	standard length
120	SFPF	Skinner Fish Protection Facility
121	SRWTP	Sacramento Regional Water Treatment Plant
122	SSC	suspended sediment concentration
123	SWP	State Water Project
124	TFCF	Tracy Fish Collection Facility
125	TNS	Tow Net Survey

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An updated conceptual model for delta smelt: our evolving understanding of an estuarine fish

By Management, Analysis, and Synthesis Team

Executive Summary

**UNDER DEVELOPMENT - No text provided pending revisions in response to review
comments**

Chapter 1: Introduction

Estuarine ecosystems are naturally complex and can be altered by a broad range of human activities with temporally and spatially variable effects on ecological processes (Townend 2004, Lotze et al. 2006, Cloern and Jassby 2012). The San Francisco Estuary (SFE; fig. 1) is one of the most well studied estuaries in the world (e.g., Conomos 1979, Hollibaugh 1996, Feyrer et al. 2004) and many of the morphological, hydrological, chemical and biological alterations that have taken place have been recognized (Nichols et al. 1986, Arthur et al. 1996, Brooks et al. 2011, NRC 2012, Whipple et al. 2012, Cloern and Jassby 2012). These alterations include diking and draining of the historical wetlands, large-scale water diversions from the southwestern Delta into the California State Water Project (SWP) and the Federal Central Valley Project (CVP), inputs of contaminants, and species introductions. As a wide variety of non-native plants and animals have invaded and become established in the SFE (Cohen and Carlton 1995, Light et al. 2005, Winder et al. 2011), native fish populations have declined (Bennett and Moyle 1996, Brown and Moyle 2005, Sommer et al. 2007).

Figure 1. Map of the San Francisco estuary. The inset shows various values of X2, the distance in kilometers from the Golden Gate to the near bottom salinity 2 isohaline.

Among the native fishes of the upper SFE (fig. 2), the endemic delta smelt (*Hypomesus transpacificus*) is of high management concern because of a decline of abundance to persistent low levels (fig. 3). Delta smelt belong to the family Osmeridae (smelts) which includes six other genera of small marine and estuarine anadromous fishes. The other native osmerid fishes commonly found in the upper SFE is longfin smelt (*Spirinchus thaleichthys*) which regularly spawns in the Delta. Similar to salmonids, some osmerid fishes have landlocked populations that may spawn in lakes or migrate to tributaries for spawning. This includes, for example, the landlocked longfin smelt population in Lake Washington, WA, and wakasagi (*Hypomesus nipponensis*), which was introduced into Central Valley reservoirs from Japan in 1959 and expanded into the Delta by as early as 1974 (Bennett 2005).

The delta smelt is a slender-bodied pelagic fish with a maximum size of about 120 mm standard length (SL) and a maximum age of two years. It is the most estuary-dependent of the native fish species in the SFE (Moyle et al. 1992, Bennett 2005). Most delta smelt complete the majority of their life cycle in the low salinity zone (LSZ) of the upper estuary and use the freshwater portions of the upper estuary primarily for spawning and rearing of larval and early post-larval fish (fig. 4; Dege and Brown 2004, Bennett 2005). Some delta smelt are also found in the freshwater portion of the estuary year round, but rarely are observed outside of the estuary and the lowest reaches of its tributaries except during spawning season, when they are sometimes captured immediately north of the Delta (Sommer et al. 2011a, Merz et al. 2011, Sommer and Mejia 2013). The continued existence of the species is dependent upon its ability to successfully grow, develop, and survive in the SFE.

Figure 2. Map of the upper San Francisco estuary. The upper estuary includes the Suisun Bay region and the Sacramento-San Joaquin Delta, which are west and east of Chipps Island respectively. The area from approximately Chipps Island to the west end of Sherman Island is referred to as the “confluence”.

Figure 3. Delta smelt abundance index for life stages of delta smelt including the larvae-juveniles (20 mm Survey), juveniles (Summer Townet Survey), subadults (Fall Midwater Trawl), and adults (Spring Kodiak Trawl),

Figure 4. Simplified life cycle of delta smelt (modified from Bennett 2005).

Delta smelt is currently protected under both California and federal endangered species legislation. The conflicts between measures intended to protect and recover the species and actions to provide water and other natural resources to humans have resulted in repeated attempts to reconcile these seemingly irreconcilable objectives. Most recently the California Delta Stewardship Council (DSC) was created to address the co-equal goals of providing a more reliable water supply for California and protecting, restoring, and enhancing the Delta ecosystem by completing and implementing a comprehensive Delta Plan (CA Water Code §85054, <http://deltacouncil.ca.gov/>). Multi-agency efforts are also underway to complete the Bay-Delta Conservation Plan, which is a large-scale plan to implement habitat restoration measures, stressor reduction activities, improved water project operations criteria, and new water conveyance infrastructure, in return for regulatory agency approval of the necessary long-term permits for the various projects and water operations to proceed over a 50-year time frame (<http://baydeltaconservationplan.com>).

Delta smelt is not the only species currently in decline in the Delta. Longfin smelt, age-0 striped bass (*Morone saxatilis*), and threadfin shad (*Dorosoma petenense*) declined simultaneously with delta smelt (the pelagic organism decline; POD) (Sommer et al. 2007, Baxter et al. 2008, 2010) (fig. 5).

Given the very different life histories of these four pelagic species, it is unlikely that a single environmental variable could account for the POD declines. In general, researchers have suggested that the POD declines were likely multi-causal (Sommer et al. 2007, Baxter et al. 2008, 2010, Mac Nally et al. 2010, NRC 2012); although, some researchers have suggested that single variables may have particular or even primary importance (e.g., Glibert et al. 2011). Moyle and Bennett (2008) and Baxter et al. (2010) suggested that the SFE, particularly the Sacramento-San Joaquin Delta (Delta, fig. 2) has undergone an ecological regime shift. Specifically, the Delta has changed from a pelagic-based estuarine system with variable salinity on seasonal and annual scales to a system reminiscent of U.S. southeastern reservoirs. In the present system an invasive aquatic macrophyte (*Egeria densa*) dominates the littoral areas of many areas of the Delta and provides ideal habitat for many invasive fishes (e.g., largemouth bass *Micropterus salmoides*; Brown and Michniuk 2007); invasive clams (*Potamocorbula amurensis* and *Corbicula fluminea*) consume a large portion of the available pelagic phytoplankton (Alpine and Cloern 1992, Lopez et al. 2006, Lucas et al. 2002, Lucas and Thompson 2012); and current management of water for agricultural, industrial and urban purposes is focused on stabilizing flow and salinity regimes to optimize water exports by the federal Central Valley Project (CVP) and State Water Project (SWP).

Many of the changes in the SFE have been documented by long-term monitoring surveys conducted by the Interagency Ecological Program (IEP). Long-term IEP surveys reveal that the abundance of delta smelt has greatly declined since the first long-term pelagic fish monitoring survey began in summer 1959 (fig. 3). Both a gradual, long-term decline and step changes, most recently around 2002, have been described using a variety of qualitative and statistical approaches for subadult delta smelt caught in the fall (e.g., Bennett and Moyle 1996, Bennett 2005, Manly and Chotkowski 2006, Thomson et al. 2010). These declines have not been smooth or entirely unidirectional and also

include a great deal of interannual variability (fig. 3). Since the beginning of the POD in 2002, the delta smelt population indices have often been at record low levels, leading to concerns that the population might now be subject to “Allee” effects (Baxter et al 2010) and may have lost its resilience, meaning its ability to recover to higher population abundances when conditions are suitable. Delta smelt had previously rebounded from low population abundances during wetter years. The lack of increase in delta smelt in the wet year of 2006 was thus a source of great concern. However, during 2011, the next wet year after 2006, the species did increase in abundance (fig. 3). Unfortunately, the increase in delta smelt abundance was short-lived and did not carry over into the following year-class in 2012, a drier year.

Figure 5. Abundance indices from fall midwater trawl for delta smelt, longfin smelt, age-0 striped bass, and threadfin shad.

The abundance increase in 2011 was intensively studied as a result of the Fall Low Salinity Habitat (FLaSH) study program associated with adaptive management of fall outflow to protect delta smelt and water supply required in a 2008 FWS 2008 Biological Opinion on the long-term operations of the Central Valley Project (CVP) and the State Water Project (SWP) (USFWS 2008).. The FLaSH studies were focused on the importance of changing fall (September to December) habitat conditions to delta smelt in response to adaptive management of fall outflow from the Delta (Reclamation 2011, 2012; see also <http://deltacouncil.ca.gov/science-program/fall-low-salinity-habitat-flash-studies-and-adaptive-management-plan-review-0>). In this report we expand the FLaSH approach to all seasons of the corresponding years to include the complete life cycle of delta smelt, and we further consider available information for the most recent year, 2012. This approach also allows us to take advantage of additional information gathered specifically for FLaSH. The specific objective of this report is to address the following questions:

- 1) Why did delta smelt abundance increase in the wet year of 2011?
- 2) Why did delta smelt fail to respond to wet conditions in 2006?
- 3) Why did the strong year class of delta smelt produced in 2011 fail to produce a large number of adult fish in the following year class of delta smelt?

Given that recovery of delta smelt and other listed and unlisted native species will be a key requirement of any plan to manage the resources of the SFE, understanding the factors affecting fish abundance is a major goal of resource management agencies. The broader goal of this report is thus to update previously developed conceptual models (CMs) for delta smelt to include our current understanding of these factors and of delta smelt responses to these factors. The updated conceptual model presented in this report is intended to serve as a framework and basis for:

- 1) organizing, analyzing, synthesizing, and communicating results about delta smelt responses to changing habitat conditions;
- 2) quantitative modeling of delta smelt responses to varying habitat conditions;
- 3) evaluating additional data and information needs concerning delta smelt;
- 4) a wide variety of management actions targeting delta smelt, including adaptive management of fall outflow, entrainment into water diversions, habitat restoration, etc.;
- 5) identifying key “indicator” variables that can be used to track and predict the status of delta smelt and its habitat and serve as “performance metrics” to evaluate the success of management actions.

Fall outflow management is currently the only active adaptive management aimed primarily at benefiting delta smelt while also protecting water supply. We anticipate that the CM in this report will

be immediately useful to this ongoing effort, including as a response to the recommendation by the independent “FLaSH Panel” of national experts convened by the Delta Science Program to:

“develop a schematic version of the CM that matches the revised, written version of the CM in the draft 2012 FLASH study report. The CM in written and schematic form should continue to emphasize processes and their interactions over simple correlations, should ensure delta smelt vital rates remain central to thinking, and should be designed for routine use by scientists as an organizational tool and for testing hypotheses associated with the AMP; it should be as complex as necessary to achieve these purposes. The CM should also be able to encompass processes and interactions that extend before and after Fall Outflow Action periods, including areas both upstream and downstream of the LSZ” (FLaSH Panel 2012, page ii).

Chapter 2: Conceptual Models

Overview

Conceptual models (CMs) are essential tools for summarizing, synthesizing, and communicating scientific understanding of ecosystem structure and functioning. They are also key to successful planning and implementation of ecological research and quantitative modeling as well as to adaptive management and restoration of ecosystems (e.g., Thom 2000, Ogden et al. 2005).

Over the last decade, two integrated sets of CMs have been developed for portions of the SFE. The first CM set was developed by the Ecosystem Restoration Program (ERP; <http://www.dfg.ca.gov/ERP/>) to evaluate restoration actions in the Delta under the “Delta Regional Ecosystem Restoration Implementation Plan” (DRERIP; DiGennaro et al. 2012). DRERIP CMs were developed for ecological processes, habitats, specific species, and stressors. The DRERIP CMs were built around environmental drivers, their expected effects termed “outcomes,” and cause- and-effect

relationships between the two shown as one-way arrows termed “linkages”. The DRERIP species CMs include “transition matrix” diagrams depicting how environmental drivers affect the probability of one life stage transitioning to the next.

The second set of CMs was developed by the IEP as a comprehensive conceptual framework intended to guide investigations of the POD and to synthesize and communicate results (Sommer et al. 2007, Baxter et al. 2010). This framework includes a “basic” POD CM about key drivers of change in pelagic fish and their habitat (fig. 6), more narrowly focused “species-specific” CMs about drivers affecting the different life stages of the four POD fish species (e.g., fig. 7), and a broader “ecological regime shift” CM (not shown; see Baxter et al. 2010). The broad scale of the ecological regime shift CM makes it not directly relevant to this report.

Figure 6. The basic conceptual model for the pelagic organism decline (Baxter et al. 2010)

Figure 7. Species-specific conceptual model for delta smelt (Baxter et al. 2010)

The National Research Council Panel to Review California's Draft Bay Delta Conservation Plan (NRC Panel) (NRC 2012) called the POD CM framework “an important example of supporting science. This framework identifies and links, in the context of both ecosystem structure and functioning, the key stressors that help to explain the decline of pelagic organisms.” The NRC Panel further noted that “the “drivers of change” identified in the POD CMs “are quantifiable” and “suitable for model evaluation” and that the:

“types of stressors identified are integrative, reflecting co-occurring physical, chemical, and biotic changes. They also apply to multiple structural (food web structure, biodiversity) and functional (food transfer changes, biogeochemical cycling) changes taking place in the Delta. The framework and associated detail are both comprehensive and useful in terms of linking these drivers to changes

taking place at multiple levels of the food web. This type of conceptual approach will also be useful for examining other drivers and impacts of ecological change, including observed changes in fish community structure and production; specifically, how these changes are affected and influenced by changes in physico-chemical factors (e.g., salinity, temperature, turbidity, nutrients/ contaminants) and at lower trophic levels (phytoplankton, invertebrate grazers, and prey)” (NRC 2012, p. 34-35).

Since the release of the 2012 NRC report, the POD CM framework has been used as the basis for additional CMs developed to aid planning and quantifying the ecological effects of active adaptive management of Delta outflow to improve fall low salinity habitat for delta smelt (Reclamation 2011, 2012). A complete summary of the POD and FLaSH CMs along with additional information about related conceptual and quantitative models in the SFE can be found in Brown et al. (unpublished data, see also <http://deltacouncil.ca.gov/science-program/fall-low-salinity-habitat-flash-studies-and-adaptive-management-plan-review-0>).

Numerous other conceptual and quantitative models have been developed for the SFE. Kimmerer (2004) summarized many of the earlier CMs. More recent CM examples include those by Glibert (2012) and Glibert et al. (2011) as well as by Miller et al. (2012). Recent examples of quantitative models include models based on statistical approaches (e.g., Manly and Chotkowski 2006, Feyrer et al. 2007, Nobriga et al. 2008, Feyrer et al. 2010, Thomson et al. 2010, Mac Nally et al. 2010, Miller et al. 2012). There is also a rapidly developing body of life cycle models for various fish species (e.g. Blumberg et al. 2010, Maunder and Deriso 2011, Massoudieh et al. 2011, Rose et al. 2011).

An Updated Conceptual Model for Delta Smelt

The CM for delta smelt in this report build on the previously developed POD and DRERIP CMs. Specifically, we modify and update the species specific POD CM for delta smelt presented in Baxter et

al. (2010) and build on the DRERIP “transition matrix” models to further explore how environmental drivers are affecting seasonal habitat and life stage transitions of delta smelt. The conceptual modeling approach in this report is not meant as a substitute for the development or use of quantitative life cycle models (e.g., Maunder and Deriso 2011). The conceptual modeling approach should be considered as complementary to the quantitative approach, identifying processes that should be considered in the quantitative models.

The CM presented here in written and schematic form is intended to emphasize processes and their interactions over simple correlations, ensure that delta smelt vital rates remain central to thinking, and be useful to scientists as a routine organizational tool for testing hypotheses associated with the management actions. The CM includes processes and interactions during the entire year for all life stages of delta smelt, rather than focusing on specific time periods or regions, such as the fall low salinity zone (LSZ) emphasized by FLASH.

Baxter et al. (2010) developed species specific models to explore and communicate differences in drivers hypothesized to affect different life stages of the four POD species. These models identified key seasonal drivers in red, with proximal causes and effects in yellow (fig. 7). For the new delta smelt CM, we modified the diagram in Baxter et al. 2010 (fig. 7) to be more consistent with the basic POD CM (fig. 6) by placing delta smelt responses (fig. 8; box with dark blue shading) in the middle of a box representing their habitat (fig. 8; light blue shading). Proximal causes are presented in this new delta smelt CM as key habitat attributes which determine habitat quality and quantity for delta smelt. Surrounding the habitat box are key environmental drivers (fig. 8; purple shading) affecting delta smelt and their habitat. Similar to the diagram in Baxter et al. 2010 (fig. 7), the CM is divided vertically and horizontally into four sections representing four delta smelt life stages occurring in four “life stage seasons” indicated in the margins of the diagram (fig. 8; green shading). Importantly, these life stage

seasons are not exactly the same as calendar-based seasons. Instead, they have somewhat variable duration and overlapping months. This is because life stage transitions from eggs to adults are gradual and different life stages of delta smelt often overlap for a period of one to three months.

Figure 8. A new conceptual model for delta smelt showing delta smelt responses (dark blue box) to habitat attributes (light blue box), which are influenced by environmental drivers (purple box) in four “life stage seasons” (green box).

Similar to the POD and DRERIP CMs, the new delta smelt CM includes only those drivers with plausible mechanistic linkages to outcomes, which in this case are changes in habitat attributes and delta smelt responses. These mechanistic linkages are depicted as one-way arrows in a series of four new life stage “transition CMs” (figs. 9 – 12) that focus on each life stage in the overall delta smelt CM. Elements of the transition CMs are grouped in the same way as the elements of the new delta smelt CM: delta smelt responses are shown at the top (dark blue shading); habitat attributes affecting delta smelt in the middle (light blue shading); and environmental drivers at the bottom of each diagram (purple shading). This grouping and arrangement of factors affecting delta smelt in horizontal tiers is more similar to the horizontally tiered “effects hierarchy” in Miller et al. (2012) than to the more vertical and less explicitly tiered arrangement of drivers in the DRERIP transition matrix CMs (DiGennaro et al. 2012).

Figure 9. Conceptual model of transition from delta smelt adults to larvae.

Figure 10. Conceptual model of transition from delta smelt larvae to juveniles.

Figure 11. Conceptual model of transition from delta smelt juveniles to subadults.

Figure 12. Conceptual model of transition from delta smelt subadults to adults.

By definition, habitat is the sum of all physical and biological attributes affecting the survival of an organism, population, or species (Hall et al. 1997). In the transition CM diagrams, the blue arrows pointing upward from individual habitat attributes thus combine into one vertical arrow pointing toward the grey horizontal arrow depicting the probability that delta smelt will successfully transition (e.g., grow, survive, reproduce) from one life stage to the next. In contrast, the linkages from environmental drivers to habitat attributes are more complex. Environmental drivers often affect more than one habitat attribute, but not all drivers directly affect each habitat attribute, as shown by the purple arrows pointing from environmental drivers to habitat attributes. Moreover, environmental drivers also interact with each other in complex ways. Some of the key interactions among the environmental drivers are shown as black arrows at the bottom of the diagrams. The relationships among environmental drivers and with habitat attributes are considered in detail in Chapter 4.

Delta smelt responses to habitat attributes as depicted in the four transition CM diagrams are explored in detail in Chapter 5 for each life stage. Each life stage section starts with an overview of delta smelt life history and population trends for the particular life stage and then explores a series of hypothesized habitat attribute-outcome linkages by comparing data pertaining to habitat attributes and delta smelt responses (outcomes). We focus these comparisons on four recent years with contrasting hydrology: the two most recent wet years (2006 and 2011) and the two drier years immediately before them (2005 and 2010). This comparative approach and data sources (described in detail in chapter 4) are deliberately similar to the comparative approach used in the FLaSH investigation (Brown et al, unpublished data, see also <http://deltacouncil.ca.gov/science-program/fall-low-salinity-habitat-flash-studies-and-adaptive-management-plan-review-0>). This allows us to place the results of the FLaSH investigation in a year-round, life cycle context and to more comprehensively evaluate factors that may have been responsible for the strong delta smelt abundance and survival response in 2011.

Individual hypotheses are indicated in the transition CM diagrams next to the arrows depicting each hypothesized linkage or outcome. While all linkages are considered important, we only developed hypotheses for linkages with sufficient data for quantitative assessments and where there is disagreement or uncertainty regarding the outcome resulting from a driver; thus, not all arrows in the diagrams have associated hypotheses.

Key insights from the four life stage sections in Chapter 5 are summarized in Chapter 6 using the new year-round delta smelt CM. Chapter 6 also includes a brief update on results for 2012, and a discussion of possible next steps in delta smelt investigations, the MAST process and future adaptive management, synthesis, and quantitative or semi-quantitative lifecycle modeling efforts aimed at delta smelt and other species.

NOTE TO REVIEWERS OF THE JULY 2013 DRAFT MAST REPORT:

Chapter 6 remains under development. At this time, only an outline is available for review. Final text will be developed after revisions to the conceptual framework and evaluation of hypotheses in response to review comments.

Chapter 3: Approach

General Approach

Our general approach in this report is to update the previously developed CMs for delta smelt and then use the updated CM as a framework to a) organize and synthesize existing knowledge about environmental drivers and key habitat attributes that affect delta smelt (Chapter 4) and b) formulate and evaluate hypotheses about the mechanistic linkages between habitat attributes and delta smelt responses

(Chapter 5). Chapter 4 includes some new analyses of long-term monitoring data, but is largely based on a review of the existing published literature. In Chapter 5, delta smelt responses to habitat attributes are explored in more detail for each life stage using a simple comparative approach. Each life stage section starts with an overview of delta smelt life history and population trends for the particular life stage and then explores a series of hypothesized driver-outcome linkages by comparing data pertaining to habitat attributes (drivers) and delta smelt responses (outcomes) in four recent years with contrasting hydrology: the two most recent wet years (2006 and 2011) and the two drier years immediately before them (2005 and 2010). In each of the sections in Chapter 5 covering a specific life stage, the hypotheses inherent in the conceptual model are stated and the reasoning for including each hypothesis is explained. Although we attempted to develop independent hypotheses, this was not always possible because many drivers were related and important habitat attributes were influenced by multiple drivers and their interactions, as shown in the CM diagrams and explored in Chapter 4

It is important to note that the updated CM that forms the basis for all analyses and syntheses presented in this report is based on the MAST's collective prior knowledge and understanding of delta smelt and the estuary and does not necessarily include all drivers and processes affecting delta smelt. The intent is to clearly state the hypotheses about important processes thought to drive delta smelt abundance and determine the amount of available information to support those hypotheses for the four study years. For this reason, the hypotheses are stated as research (alternative) hypotheses rather than null hypotheses. Future steps in this iterative process should include additional years and identify additional processes deserving of focused study. New information from such studies should drive revision of the conceptual model as new knowledge becomes available. Ideally, this should lead to additional hypothesis-driven adaptive management experiments similar to the fall outflow adaptive management program and the associated FLaSH studies. Individual hypotheses are indicated in the

transition CM diagrams (figs. 9-12) next to the arrows depicting each hypothesized linkage or outcome. While all linkages are considered important, only linkages with sufficient data for quantitative assessments and where there is disagreement or uncertainty regarding the outcome resulting from a driver are explored via hypotheses; thus, not all arrows in the diagrams have associated hypotheses. For each of these hypotheses, we then considered the available data to examine whether the delta smelt response was consistent with the observed trends in habitat attributes or population dynamics. Note that we have not examined the complex interactions that may have occurred when more than one hypothesis was true (or false), nor have we ruled out that an hypothesis may be true in some years and false in others. Therefore, it is important to recognize that data contrary to a hypothesis may indicate that the habitat attribute wasn't controlling in the selected years, or that complex interactions among multiple habitat attributes (and corresponding hypotheses) contributed to the observed effects.

If the data needed to evaluate a hypothesis were not available or is inconclusive, the type of data needed to assess the hypothesis is described and summarized in Chapter 6 so studies to test the hypothesis can be designed and made available to appropriate agencies for potential implementation.

As mentioned in Chapter 2, the simple comparative approach and data sources used in Chapter 5 are deliberately similar to the comparative approach used in the FLaSH investigation, but that effort was focused on the fall season (Sep-Dec) (for details see <http://deltacouncil.ca.gov/science-program/fall-low-salinity-habitat-flash-studies-and-adaptive-management-plan-review-0>). It is, however, important to keep in mind that the FLaSH investigation is part of an active, hypothesis-driven adaptive management experiment with intentional manipulation of Delta outflow in the fall aimed at testing predictions derived from hypotheses formulated before the start of the manipulations. The analyses presented in this report are also based on hypotheses, but with the exception of the fall outflow manipulation, there are no other experimental manipulations to test these hypotheses.

Key insights from Chapters 4 and 5 are summarized in Chapter 6 using the new year-round delta smelt CM. Based on these insights, we also present some ongoing or possible next steps for future years, including some recommendations for the FLaSH investigation, additional data collection, and future synthesis and quantitative or semi-quantitative lifecycle modeling efforts aimed at delta smelt and other species. Finally, we use data from 2012 to evaluate the most recent data available. This serves as a preliminary, limited validation of the new conceptual model.

Data Sources and Analyses

Our examination of environmental drivers in Chapter 4 and the evaluation of hypotheses in Chapter 5 rely largely on environmental monitoring data collected by IEP agencies during routine, long-term monitoring surveys. These surveys provide the long-term records and geographic coverage necessary and the data collected by these surveys are publicly available. Use of these particular data sources does not reflect any preference for those data. Results from other ongoing research efforts were included as appropriate.

For the purposes of this report, we consider each stage of the delta smelt life cycle in the context of the monitoring programs that provide data on the delta smelt population. Specifically, late winter and spring include the spring Kodiak trawl (SKT), which samples mature, spawning and post-spawning adults. The SKT is conducted from January through May. Spring also includes the 20-mm survey (20-mm), which samples post-larval delta smelt and is conducted from mid-March through mid-July. Summer includes the summer townet survey (TNS); which samples juvenile fish and currently runs from June through August. Fall and early winter are defined by the months of the Fall Midwater Trawl (FMWT) survey, which samples subadult delta smelt and begins in September and ends by mid-December.

As noted previously, our approach is comparative. Similar to the approach taken in the FLASH investigation (Brown in prep., see also <http://deltacouncil.ca.gov/science-program/fall-low-salinity-habitat-flash-studies-and-adaptive-management-plan-review-0>), we compare data from 2005, 2006, 2010, and 2011, which we call our “study years” for the purposes of this report. The failure of the delta smelt population to increase in the wet year of 2006 and the increase of delta smelt in 2011 followed by the decline in 2012 provides the opportunity to compare and contrast several distinct but potentially informative situations. We recognize that preceding habitat conditions may have important implications for the response of a population to the environmental conditions present during a wet year; therefore, we also consider data from 2005 and 2010. Water year 2005 was classified as “above normal” in the Sacramento Valley and “wet” in the San Joaquin Valley and 2006 was classified as wet in both areas (see <http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST>). Water year 2010 was classified as “below normal” in the Sacramento Valley and “above normal” in the San Joaquin Valley and 2011 was classified as wet in both areas (see <http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST>). Further, we also consider recruitment in 2012 following the wet year of 2011. Water year 2012 was classified as “below normal” in the Sacramento Valley and “dry” in the San Joaquin Valley.

Some graphs and analyses refer specifically to the POD period. Analyses suggest the the POD period started as early as 2002 or as late as 2004 (Thomson et al. 2010). We somewhat arbitrarily selected, 2003-present as the POD period for this report. This period is not being recommended as the baseline for management agencies to use when considering recovery of delta smelt. The time period simply reflects the consistently low level of delta smelt in recent years and a useful baseline for identifying years with improved delta smelt abundance indices, which would indicate improved environmental conditions for delta smelt.

In many cases, the data presented in this report are represented as boxplots. The center horizontal line in each box represents the median of the data. The upper and lower ends of the box represent the upper and lower quartiles of the data. These are also known as “hinges”. The “whiskers” are the lines extending above and below the box. The whiskers show the range of values falling within 1.5 times the inter-quartile distance from the nearest hinge. Values outside this range are shown as individual symbols. Other types of plots are explicitly identified in the figure caption.

Chapter 4: Environmental Drivers and Habitat Attributes

The general approach of this chapter is to focus on how environmental drivers and interactions among them create habitat attributes of importance to delta smelt. Each section focuses on a habitat attribute that can be the outcome of one or more environmental drivers. Physical habitat attributes are presented first, followed by biological habitat attributes. The order of presentation does not imply any kind of ranking of habitat attributes. We consider all habitat attributes discussed here as equally important because, as noted in Chapter 2, habitat is the sum of *all* physical and biological attributes affecting a species.

Each section starts with the general importance of a specific habitat attribute for estuarine biota followed by a brief discussion of its linkages with environmental drivers and its dynamics in space and time. Each habitat attribute is then placed in the context of delta smelt biology. Detailed discussion of delta smelt responses to habitat attributes are the subject of the life stage sections in Chapter 5.

Water Temperature

Water temperature is an important variable for ectothermic (“cold-blooded”) animals, including all fishes and invertebrates in the SFE. In the most extreme case, when water temperature exceeds the thermal tolerance of an organism, it will die. Temperatures within the thermal tolerance of an organism

control the rate and efficiency of many physiological processes, including activity, digestion, growth, reproductive development, and reproductive output. We return to these processes after giving an overview of water temperatures in the Delta.

In tidal systems, water temperature in a particular location is determined by the interaction between atmospheric forcing, tidal dispersion and riverine flows (Monismith et al. 2009). Wagner et al. (2011) developed simple regression models for predicting water temperature from environmental data. Somewhat surprisingly, good statistical models of daily water temperature were developed for fixed temperature stations using only air temperature and insolation (sunlight) on the day of interest and the water temperature from the previous day. Water temperature from the previous day accounts for both previous air temperature and the sources of water to the site, including advective flow from rivers or dispersive flow from more downstream reaches of the SFE. Each model had a different set of coefficients because of the differing influences of incoming river water or tidal exchange with San Francisco Bay. For stations with greater than 1 year of calibration data, model R^2 for daily average temperature exceeded 0.93, indicating that water temperature was highly predictable. High winter and spring flows were responsible for the largest divergences of the model outputs from measured temperatures. In addition to source water, the results suggest that air temperature and insolation are the major drivers of water temperature variation under most conditions (Wagner et al. 2011). These simple statistical models should be used with caution because they only predict temperature at the site of the recording instrument. There are important lateral and vertical variations in temperature on daily time scales (Wagner 2012) that could be important to organisms. For example, such variation might include formation of important thermal refugia.

Long term temperature records from selected sites show substantial seasonal and daily fluctuations in water temperature (Kimmerer 2004). While daily variations are evident and likely

important to organisms, seasonal variations are much greater (Wagner 2012). Median water surface temperatures across all stations monitored by the IEP Environmental Monitoring Program (EMP) from 1975-2012 range from 9°C in January (minimum: 6°C) to 22°C in July (maximum: 28°C).

Regional variations are also evident. For example, water surface temperatures collected at the IEP Summer Townet Survey stations during June-August of the comparison years were lowest at stations with salinity >6 and in the low salinity zone, and higher at stations in the freshwater regions of the estuary, including the Cache Slough region in the North Delta (fig 13). At Antioch, the approximate center of the delta smelt distribution in the late summer and fall, seasonal variation in daily average temperature ranges from about 10°C to 24°C.

There is currently little evidence for increasing water temperatures in the Delta associated with climate change, although such increases are expected over the course of the century (Cloern et al. 2011, Brown et al. 2013). In Spring (March-June) water temperature at IEP EMP water quality monitoring stations in the Delta increased during 1996–2005 by about 0.2°C per year ($^{\circ}\text{C y}^{-1}$), but a similar trend was not apparent for the longer-term data record from 1975-2005 or for stations in Suisun Bay (Jassby 2008). These findings are similar to the results of Nobriga et al. (2008) who found no long-term trends in temperature data collected during summer fish monitoring surveys in the Delta. Nobriga et al. (2008) also noted that the long-term (1970-2004) mean July water temperature at stations in the San Joaquin region of the Delta is 24°C, with current mid-summer temperatures often exceeding 25°C

Upper temperature limits for juvenile delta smelt are based on laboratory and field data. Interpretation of the laboratory results is somewhat complicated as temperature limits can be affected by various factors including acclimation temperature, salinity, turbidity and feeding status. However, juvenile delta smelt acclimated to 17°C could not tolerate temperatures higher than 25°C (Swanson et al. 2000), a level that is highly consistent with water temperatures measured during field collections of

juvenile delta smelt (Nobriga et al. 2008). In addition to lethal effects, water temperature also has direct effects on the bioenergetics (interaction of metabolism and prey density) of delta smelt (Bennett et al. 2008) and it may affect their vulnerability to predators. The maximum temperature delta smelt will tolerate is currently being revisited as part of a larger UC Davis study about the “fundamental niche” of delta smelt, but results have not yet been published.

The topic of bioenergetics is an important consideration in much of the remainder of this paper, so we address it in more detail here. In general, the total metabolic rate of a fish will increase with temperature to an optimum temperature at which, given unlimited food, there is the maximum ability to grow and develop reproductive products (eggs or sperm) in addition to maintaining the basal metabolic rate required for survival, which is also increases with increasing temperature (Houde 1989, Hartman and Brandt 1995). As temperature increases beyond the optimum, metabolic rate continues to increase but physiological processes become less and less efficient and more energy is required just to meet the basal metabolic rate of the organism. Eventually, the metabolic rate begins to decline as temperatures go beyond the physiological limits of the organism and the basal metabolic rate can no longer be maintained. At higher temperatures the organism will die quickly. At the stressful temperatures beyond the optimum but below the lethal level, the ability to grow and mature might be impaired or over some period of time could be lethal. In addition, resistance to disease and contaminants could be affected. The previous description assumes unlimited food, which is unlikely to be the case for delta smelt or any organism in nature. Even at the optimum temperature, growth and reproductive development will depend on the quantity and quality (energy and nutrient content) of the food consumed. If the fish is unable ingest enough food to meet its nutrient and energetic requirements, including the energy expended to capture and digest prey, it will starve, after first depleting any available energy stores (fat or muscle). Given an array of food items, fish will often chose the largest prey item that it is able to

consume. This is because the energy required to detect, chase, and capture multiple smaller prey that are equivalent in nutritional value to a single large prey item will, in many cases, exceed the energy required to capture the single prey item. Note that these same ideas apply to predatory fish that might consume delta smelt.

Water temperature is thought to affect the abundance of eggs produced by female delta smelt. Abundance of eggs is influenced by not only female size and number (Bennett 2005, DFW unpublished), but also by the duration of a temperature “spawning window” (Bennett 2005, Mac Nally et al. 2010), variously defined as: 15-20°C by Bennett (2005); 7-15°C by Wang (1986); and 12-15°C by Baskerville-Bridges et al. (2004b). Bennett (2005) further stated that during cool springs this spawning window persists longer, allowing more cohorts to recruit. Given a sufficiently long spawning window, individual females may also repeat-spawn during the spawning season. This has been documented in culture (see Bennett 2005; J. Lindberg, U.C. Davis, pers. comm. 2013) and appears to occur in the wild as well (L. Damon, CDFW, pers comm. 2012). Lindberg (U.C. Davis, pers. comm. 2013) observed that most females in culture spawned twice, some spawned three times and a very small number spawned four times. Each spawning was separated by a 4-5 week refractory period during February through June when water temperatures remained within the spawning window. Though such protracted spawning conditions may not occur in the wild, ripe females ready to release their second complete batch of eggs and developing a third batch have been detected in the wild during March and April (i.e., mid-season) suggesting that three spawns are possible (L. Damon, CDFW, pers. comm. 2012). Thus, a longer spawning window would allow more females to repeat spawn adding both additional cohorts hatching under different conditions, but also multiplying the fecundity of each repeat spawner (i.e., increasing total fecundity of the individual), and total fecundity of the population. Moreover, in culture, individual females continued to grow through the spawning season and become more fecund with each batch of

eggs (J. Lindberg, U.C. Davis, pers. comm. 2013). In the wild, the size of mature females increased month to month through the spawning season (L. Damon, CDFW, pers. comm. 2012), suggesting the potential increase in fecundity with each batch, but this has yet to be confirmed. However, in culture, fish hatched later in the spawning season (mid-May to mid-June) grew up to be smaller-sized adults that started spawning later and had progeny with lower survival than the progeny of fish hatched earlier in the season (Lindberg et al. 2013). The effect of a prolonged spawning season on delta smelt population size and dynamics thus remains uncertain.

In the culture experiments reported by Bennett (2005), temperature strongly influenced hatching success of eggs, which appeared optimal at about 15°C and declined rapidly at higher and lower temperatures. Furthermore, as incubation and early rearing temperatures increased, size at hatching and size at first feeding linearly decreased possibly because basal metabolism used more energy leaving less for growth. Starting life after hatching at a relatively small size in relatively warm temperatures late in the season may have negative implications for larval survival. First, small size would limit the size of food items that the larvae could ingest because of smaller mouth sizer (see Nobriga 2002), and second, small larvae are likely vulnerable to a larger range of predators for a longer period compared to larger larvae (e.g., ‘stage duration hypothesis’, Anderson 1988). Temperature may also affect food type and availability as discussed below.

As explained above, higher water temperatures increase energetic requirements and thus the food requirements of delta smelt. To meet the increased need for food, the time delta smelt spend foraging during the day likely increases. Since greater foraging time increases visibility to predators, the net effect is an increase in their predation risk (e.g. Walters and Juanes 1993). At the same time, evidence from other fishes suggests that high temperatures can decrease antipredator behavior (as described for Sacramento River Chinook salmon by Marine and Cech 2004). In other words, the fish

make a behavioral choice to feed, grow, and become less vulnerable to predators, even though the short-term predation risk might increase. Another possible indirect effect of higher water temperatures is that they may promote harmful algal blooms (HAB) (Lehman et al. 2005), which may degrade delta smelt habitat quality (Baxter et al. 2010). The possible effects of HABs are discussed fully in a separate section of this Chapter.

During the fall months, water temperatures in the estuary seldom exceed 25°C and temperatures decline rapidly between October and December (fig. 14). However, subadult delta smelt appear to have a physiological optimum temperature near 20°C (Bennett et al. 2008, Nobriga et al. 2008), a temperature which is exceeded during September and October at some times and places in some years (fig 14). Thus, we suggest that the same tradeoffs between feeding and predation risk also apply during the warmer months of the fall. Similarly, any negative effects of HABs may also apply.

The combination of substantial direct and indirect effects of water temperature for all life stages of delta smelt means that this variable should be considered one of the most important habitat attributes for delta smelt. Differences in water temperature between regions or time periods may have important effects on the delta smelt population.

Figure 13. Surface water temperature (°C) data collected during the Summer Townet Survey. Surveys are conducted biweekly June - August.

Figure 14. Surface water temperature (°C) data collected during the Fall Midwater Trawl Survey. Surveys are conducted monthly September - December.

Size and Location of the Low Salinity Zone

A salinity gradient from fresh water to salt water, is one of the most characteristic features of an estuary. The brackish “low salinity zone” (LSZ) is an important region for retention of organisms and

particles and for nutrient cycling. In the SFE, the LSZ (salinity 1-6 in this report) provides important habitat for numerous organisms including delta smelt (Turner and Chadwick 1972, Kimmerer 2004, Bennett 2005). The position of the LSZ is commonly expressed in terms of X2, which is the distance from the Golden Gate in km along the axis of the estuary the salinity 2 isohaline measured near the bottom of the water column (Jassby et al. 1995). The intent of using X2 as an index was to develop an easily-measured, policy-relevant indicator with ecological significance for multiple species and processes (Jassby et al. 1995). In this context, the position of the LSZ as indexed by X2 is more easily measured than delta outflow because under most circumstances tidal flows are much larger than the net outflow, making net flows difficult to determine from field measurements.

The size and location of the LSZ is a key factor determining the quantity and quality of low salinity rearing habitat available to delta smelt and other estuarine species. LSZ size and location are determined by the interaction of dynamic tidal and river flows with the stationary topography of the region (Reclamation 2011, 2012). At high Delta outflows (low X2), the LSZ can be located as far west as San Pablo Bay. At intermediate outflows (intermediate X2), it is located east of Carquinez Strait and covers a large area that includes the shallow, open Suisun Bay and parts of Suisun Marsh (fig. 15). At lower outflows (high X2), the LSZ occupies a smaller area that includes the deep and spatially more constricted confluence of the Sacramento and San Joaquin Rivers (fig. 16). Historically, the LSZ moved according to a predictable annual rhythm from the west in winter and spring to the east in summer and fall (fig. 17). Interannual variations in precipitation and hence river flows caused a high degree of interannual variability in these seasonal shifts (Dettinger 2011). Over the last 150 years, human flow manipulations and landscape alterations have greatly changed the location, extent, and dynamic movements of the LSZ and its interactions with other parts of the estuary. The seasonal and interannual variations have become muted, especially in the summer and fall (fig. 18).

882 **Figure 15.** Salinity distribution at intermediate outflow. The upper panel shows the area of the low-salinity zone
883 (9,140 hectares) at $X_2 = 74$ km (at Chipps Island). The lower panel shows the percentage of day that the low-
884 salinity zone occupies different areas.

885 **Figure 16.** Salinity distribution at intermediate outflow. The upper panel shows the area of the low-salinity zone
886 (4,262 hectares) at $X_2 = 85$ km, when positioned mostly between Antioch and Pittsburg. Connections to
887 Suisun Bay and Marsh have nearly been lost. The lower panel shows the percentage of day that the low-
888 salinity zone occupies different areas.

889 **Figure 17.** Plot of monthly X_2 (km) values calculated from mean monthly unimpaired Delta outflows from 1921-
890 2003. X_2 values are categorized by water year type for the Sacramento Valley. Also shown are the median X_2
891 values from 1921-2003 across all water year types (grey circles) C, red dots: critically dry; D, orange dots: dry;
892 BN, yellow dots: below normal; AN, light blue dots: above normal; W, dark blue dots: wet. Water year type data
893 from <http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST> . Unimpaired flow data from DWR 2007 (available at
894 [http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/bay_delta_plan/water_quality_co](http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/bay_delta_plan/water_quality_control_planning/docs/sjrf_spptinfo/dwr_2007a.pdf)
895 [ntrol_planning/docs/sjrf_spptinfo/dwr_2007a.pdf](http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/bay_delta_plan/water_quality_control_planning/docs/sjrf_spptinfo/dwr_2007a.pdf)) . X_2 equation from Jassby et al. 2005.

896 **Figure 18.** Plot of daily X_2 (km) values calculated from daily Delta outflows from 2000 to 2011 (since SWRCB
897 water right decision 1641 went into effect). X_2 values are categorized by water year type for the Sacramento
898 Valley. Also shown for comparison are the median monthly X_2 values from 1921-2003 across all water year
899 types (grey circles) C, red dots: critically dry; D, orange dots: dry; BN, yellow dots: below normal; AN, light blue
900 dots: above normal; W, dark blue dots: wet. Water year type data from [http://cdec.water.ca.gov/cgi-](http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST)
901 [progs/iodir/WSIHIST](http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST) . Unimpaired flow data from DWR 2007 (available at
902 http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/bay_delta_plan/water_quality_co

ntrol_planning/docs/sjrf_spprtinfo/dwr_2007a.pdf). Delta outflow data from DAYFLOW
(<http://www.water.ca.gov/dayflow/>). X2 equation from Jassby et al. 2005.

Delta smelt are found in the estuary at salinities up to 18 (Bennett 2005), but are most common in the in the LSZ (<6) (Sommer and Meija 2013). Sommer et al. (2011a) described delta smelt as a “diadromous species that is a seasonal reproductive migrant.” In the winter, adult delta smelt move upstream into fresh water for spawning. In the spring and summer, young delta smelt are transported or swim downstream into the LSZ. Delta smelt usually rear in low salinity habitat in the summer and fall, although some delta smelt remain year-round in fresh water (Sommer et al. 2011a, Merz et al. 2011, Sommer and Meija 2013).

The recruitment success of longfin smelt and striped bass, but not delta smelt, has been shown to increase with a more westward position of the LSZ during spring (Jassby et al. 1995). It has been hypothesized that persistent eastward location of the LSZ in the fall has negative effects on delta smelt (Reclamation 2011) based on the finding that these changes reduce habitat area for delta smelt and perhaps their abundance (Feyrer et al. 2007, 2010). Changes in the size, location, and dynamics of the LSZ likely also interact in complex ways with other changes, such as changes in sediment and nutrient loadings and resulting turbidity and nutrient dynamics and their effects on delta smelt and the food web. For example, LSZ position affects recruitment of the invasive clam *Potamocorbula amurensis*, which may in turn affect phytoplankton and zooplankton biomass, size, and production (Thompson 2005, Winder and Jassby 2010). Ongoing studies coordinated by the IEP as part of the POD and FLASH studies focus on the processes that link physics, chemistry, and biology in the LSZ and its habitat value for delta smelt and other native and non-native species.

Turbidity

Turbidity is an not a habitat attribute in the sense we use in this report because we do not show delta smelt outcomes directly resulting from responses to turbidity (figs. 8-12). Clearly, studies have shown that distribution of delta smelt is correlated with turbidity (e.g., Feyrer et al. 2007, Nobriga et al. 2008). In the CM we chose to incorporate turbidity as a modifier of several important linkages between environmental drivers and habitat attributes that are important to delta smelt, primarily food visibility for small larvae, predation risk for all life stages and spawning cues for adults. If turbidity was incorporated as a habitat attribute and, for example, predation risk was discussed separately from turbidity, there would be a great deal of overlapping text between the two sections because turbidity interacts with the presence of predators to determine predation risk. This approach is not ideal but should reduce redundant text and contribute to clarity of presentation. Nonetheless, we recognize that turbidity by itself might also be considered as a habitat attribute. For example, it is possible that delta smelt experience stress in low turbidity habitat, which would in turn affect survival (likely through predation) but also in other direct ways such as lower growth and reduced egg production. However, we do not have evidence at this point to support that hypothesis.

In addition to salinity gradients, estuaries often have turbidity gradients. Turbidity is an optical property of water, which is the loss of transparency due to scattering of light by suspended particles. Typically, the upper reaches of estuaries have areas with high levels of suspended particles known as “estuarine turbidity maxima.” In many estuaries, these areas are located in or near the low salinity zone and are recognized as particularly productive fish nurseries (Sirois and Dodson 2000a, b, Shoji et al. 2005). In the SFE, turbidity is largely determined by the amount of suspended inorganic sediment in the water (Cloern 1987, Ganju et al. 2007, Schoellhamer et al. 2012), although organic components may also play a role (U.S. Geological Survey 2008). Sediment particles are constantly deposited, eroded, and

resuspended, and are transported into, within, and out of the estuary. The amount of sediment that is suspended in the water column depends on the available hydrodynamic energy, which determines transport capacity, and on the supply of erodible sediment.

In the upper SFE there are two main sources of turbidity. High flows transport suspended sediment from the tributary watersheds into the system during high flows associated with winter and spring storm runoff. The first large storm of the rainy season often carries the highest concentrations of suspended sediment. Some portion of the transported sediment moves through the system to San Pablo and San Francisco Bay and the remainder is stored within the system as bottom sediment. During the remainder of the year, turbidity is primarily caused by interactions of this stored sediment with other environmental drivers. Water moving with the tides can resuspend fine sediments because of turbulence resulting from interactions between the bottom and water moving at high tidal velocities. At a larger scale, irregularities in the bottom topography may define geographic regions of greater turbulence and greater turbidity. In the upper estuary, such regions occur at a large bathymetric sill between Carquinez Strait and Suisun Bay and at another location within Suisun Bay (Schoellhamer 2001). Sediments may also be resuspended by turbulence related to wind waves. This process is mainly limited to areas with fine sediments on relatively shallow shoals where wind wave turbulence reaches the bottom. This process is most important in the shallows of Suisun, Grizzly, and Honker Bays and Liberty Island (Ruhl and Schoellhamer 2004, Warner et al. 2004, Morgan-King and Schoellhamer 2013). Thus, turbidity is the result of several environmental drivers, including hydrology (transport from the watershed) and weather (wind and precipitation) interacting with the physical configuration of the upper SFE. Further, annual variation in these factors may have important effects. For example, during a drought there is little transport of suspended sediment and the same wind patterns during the summer may result in less

turbidity because less sediment was stored as benthic sediment during the winter. There is also evidence of longer term changes in turbidity, along with regional differences.

Among the geographic regions of the upper SFE, the Suisun region is one of the most turbid, when the system is not being influenced by storm flows. This results from strong turbulent hydrodynamics in the Suisun region caused by strongly interacting tidal and riverine flows, bathymetric complexity, and high wind speeds, which create waves that resuspend erodible benthic sediment in the large and open shallow bays of the Suisun region. The North Delta, especially the large open expanse of Liberty Island (flooded since 1998) and the adjacent Cache Slough region are also relatively turbid. Recent evidence suggests that Liberty Island acts as a sediment sink in the winter and a sediment source for the surrounding Cache Slough complex in the summer (Morgan-King and Schoellhamer 2012).

Turbidity is usually lower in the channels of the confluence of the Sacramento and San Joaquin Rivers compared to the Suisun region and North Delta region. Turbidity dynamics in the deep channels of the river confluence are driven more by riverine and tidal processes while high wind and associated sediment resuspension has little if any effect (Ruhl and Schoellhamer 2004). Turbidity is generally lowest in the south Delta (Nobriga et al. 2008). This may in part be due to sediment trapping by large, dense beds of *Egeria densa*, an invasive species of submerged aquatic vegetation (Hestir 2010). In winter/spring during the comparison years the highest Secchi disc depths (lowest turbidity) were found in the freshwater regions of the estuary (<1 salinity), except for the Cache Slough region in the north Delta which was as turbid as the saltier regions of the estuary (fig. 19).

Figure 19. Secchi depth data collected during the 20mm Survey. Surveys are conducted biweekly March-July.

There is strong evidence for a long-term decline in sediment transport into the upper estuary (Wright and Schoellhamer 2004), leading to a long-term increase in water clarity in the upper Estuary (Jassby et al. 2002, Feyrer et al. 2007, Jassby 2008). Jassby et al. (2002) documented a 50% decrease in

total suspended-solids concentration (TSS; equivalent to suspended sediment concentration (SSC) in this estuary) in the Delta from 1975-1995. Jassby et al. (2005) showed that TSS concentrations in the north Delta dropped sharply toward the end of the 1982–1983 El Niño-Southern Oscillation (ENSO) event and did not recover afterward. Following the El Niño event of 1997–1998, there was a 36% step decrease in SSC in San Francisco Bay as the threshold from transport to supply regulation was crossed as an anthropogenic erodible sediment pool was depleted (Schoellhamer 2011). Sediment trapping by dense beds of *Egeria densa* may be further reducing available sediment in the Delta (Hestir 2010).

Before the step decline in SSC and the onset of the pelagic organism in the late 1990s and early 2000s (i.e. the “pre-POD” period), water transparency (roughly the opposite of turbidity) measured with a Secchi disc at all IEP EMP stations was usually highest in November and lowest in June (fig. 20). From 2003-2012 (i.e. the “POD” period), average water transparency was not only higher (by on average 16 cm Secchi disc depth) than in the the previous period, but the annual dynamics also shifted forward by a month, to greatest transparency (i.e. lowest turbidity) in October and lowest transparency in May. The greatest differences in average water transparency between the pre-POD and POD periods occurred in September and October (28 and 30 cm difference between monthly averages, respectively) and the smallest differences in January-May (10 cm).

Figure 20. Average and median secchi depth in cm from monthly sampling at IEP Environmental Monitoring Program stations. Data are shown for the time period up to the pelagic organism decline (1975-2002) and after the decline (2003-2012).

Delta smelt are visual feeders, and feed primarily between dawn and dusk (Hobbs et al. 2006, Slater and Baxter submitted). As for all visual feeders, visual range and prey density determine feeding success of delta smelt. Visual range depends on size, contrast and mobility of the prey, retinal sensitivity and eye size of the visual feeder, and on the optical habitat attributes such as light scattering, absorption,

and intensity (Aksnes and Giske 1993). Optical habitat attributes are affected by turbidity from suspended organic particles such as algae and detritus and inorganic particles such as sand and silt. Somewhat counterintuitively, some level of turbidity appears important to the feeding success of larval delta smelt. In laboratory experiments in which alga densities and light levels were manipulated and first-feeding success of larval delta smelt was quantified, Baskerville-Bridges et al. (2004a) found that maximum feeding response occurred at the highest alga concentrations and light levels tested. In a subsequent experiment, when algae were removed entirely, the feeding response was very low. The addition of algae or some other form of suspended particle is standard practice for successfully rearing delta smelt larvae in culture facilities (Mager et al. 2004, Baskerville-Bridges et al. 2005). Presumably the suspended particles provide a background of stationary particles that helps the larvae detect moving prey. Sufficient turbidity also appears to be important to reduce overall environmental stress and increase survival of larval delta smelt (Lindberg et al. 2013). Thus, it seems likely that turbidity is important to the feeding success and survival of larval delta smelt in the wild.

In addition to its effects on feeding, turbidity may also reduce predation risk. Based on the general recognition that fish assemblages are often partitioned between turbid-water and clear-water assemblages (Rodríguez and Lewis 1997, Whitfield 1999, Quist et al. 2004), and that turbidity can influence the predation rate on turbid-adapted fishes (Rodríguez and Lewis 1997; Gregory and Levings 1998; Quist et al. 2004), it has generally been assumed that juvenile and adult delta smelt are closely associated with turbidity in order to minimize their risk of predation in their generally open-water habitat. There may also be complex interactions between feeding and predation risk that are mediated by turbidity. Turbidity may reduce feeding rate depending on the interaction of turbidity with predation risk to feeding delta smelt (e.g, Miner and Stein 1996).

Multiple field studies have established the association between elevated turbidity and the occurrence of delta smelt. The abundance of delta smelt larvae in the 20 mm Survey was well explained by salinity and Secchi depth, a proxy for turbidity (Kimmerer et al. 2009). Nobriga et al. (2008) found that juvenile delta smelt are strongly associated with turbid water, a pattern that continues through fall (Feyrer et al. 2007). Grimaldo et al. (2009) found that the occurrence of adult delta smelt at the SWP salvage facilities was linked, in part, with high turbidity associated with winter “first flush” events.. Long term declines in turbidity may also be a key reason that juvenile delta smelt rarely occur in the south Delta during summer (Nobriga et al. 2008).

Entrainment and Transport

The egg, larval, and juvenile stages of estuarine fishes and invertebrates along with small and weakly swimming adult stages are subject to involuntary transport (advection) by riverine and tidal flows. Entrainment is a specific case of involuntary transport. It refers to situations when altered flows misdirect and transport fish and other organisms in directions in which they would not normally travel or where they will encounter unfavorable conditions and increased risk of mortality. In this report, we use the term entrainment to specifically refer to the incidental removal of fishes and other organisms in water diverted from the estuary, primarily by CVP and SWP export pumping (Castillo et al. 2012).

Ultimately, watershed hydrology determines how much water can flow into and through the Delta; however, water flows into, within, and out of the Delta are manipulated in many ways. Water is: routed through and around artificial channels, gates, and barriers; stored in and released from reservoirs; discharged from agricultural and urban drains; and diverted with large and small pumps. Perhaps the greatest flow alterations in the Delta have taken place in Old and Middle Rivers in the central Delta. Historically, these river channels were part of the tidal distributary channel network of the San Joaquin River (Whipple et al. 2012). Today, their lower reaches (collectively referred to as “OMR”) are a

central component of the CVP and SWP water conveyance system through the Delta. Water from the Sacramento River in the north now flows through the northern Delta (around Sherman Island) and eastern Delta (via the artificial “Delta cross-channel”) to OMR in the central Delta, then to the SWP and CVP. The SWP and CVP pumps are capable of pumping water at rates sufficient to cause the loss of ebb tide flows and to cause negative net flows (the advective component of flow after removal of the diffusive tidal flow component) through OMR toward the pumps, thus greatly altering regional hydrodynamics and water quality (Monsen et al. 2007). Under these conditions, fish and other aquatic species in the Delta may be transported toward the pumps, or may swim toward the pumps if they are behaviorally inclined to follow net flow.

The SWP and CVP have large fish protection facilities to reduce entrainment - the state Skinner Fish Protective Facility (SFPF) and the federal Tracy Fish Collection Facility (TFCF). The SFPF and TFCF are located at the intakes to the State and Federal export pumps on Old River in the southwestern Delta. Both facilities have fish screens that are used to capture and collect fish before they reach the pumps. The “salvaged” fish are then trucked to and released back into the western Delta. A variable fraction of these fish survive the capture, handling, trucking and release process (Aasen, in press, Afentoulis et al., in press, Morinaka, in press a). The number of salvaged fish is monitored and reported as an index of SWP and CVP salvage and entrainment losses (Morinaka, in press b, more information and data available at <http://www.dfg.ca.gov/delta/apps/salvage/Default.aspx>).

Delta smelt salvage has been recorded since 1982 (Morinaka, in press b). Similar to the TNS and FMWT results for delta smelt, delta smelt salvage has declined dramatically since the beginning of this time series (fig. 21) This is similar to trends for Chinook salmon and striped bass salvage (not shown), but opposite to trends for largemouth bass (*Micropterus salmoides*) and bluegill (*Lepomis macrochirus*) salvage (fig. 22), two species that may be profiting from conditions resulting from a hypothesized

ecological regime shift (Baxter et al. 2010). The ratio of delta smelt salvage divided by the previous year's FMWT index has been used as a simple indicator of possible entrainment losses. For adult (December-March) salvage, this ratio has been variable over time, but particularly high in the first year of this time series (1982, a wet year) and again during the beginning of a series of drought years in 1989 and in the fairly dry "POD" years 2003-2005 (fig. 23). Current management provisions to protect delta smelt (UFWS 2008) are aimed at keeping this ratio at no more than the average of the 2006-8 levels.

Figure 21. Annual time series of adult delta smelt (December-March) salvage at the CVP (blue bars) and SWP (green bars) fish protection facilities. Also shown are the delta smelt fall midwater trawl index (FMWT) from the preceding year (black line) and the combined SWP and CVP water export volume (thousands of acre feet) from October (i.e. beginning of water year) to March (blue line).

Figure 22. Annual time series of largemouth bass (top graph) and bluegill (bottom graph) salvage at the CVP (blue bars) and SWP (green bars) fish protection facilities. Also shown are the annual San Joaquin Valley Water Year Index (blue line) and the combined annual (water year) SWP and CVP water export volume (purple line; MAF, million acre feet).

Figure 23. Annual time series of the ratio of adult (December-March) delta smelt salvage at the CVP (blue bars) and SWP (green bars) fish protection facilities divided by the delta smelt fall midwater trawl index (FMWT) from the preceding year. Also shown are the combined SWP and CVP water export volume (MAF, million acre feet) from October (i.e. beginning of water year) to March (purple line).

Delta smelt were salvaged nearly year-round in the beginning of this time series, but delta smelt salvage now only occurs in December-June. This trend coincides with the near disappearance of delta smelt from the central and southern Delta in the summer (Nobriga et al 2008). Historically, adult and larval delta smelt salvage were not separately recorded and reported, but adults are predominantly

salvaged between December and March or April. Larvae greater 20 mm SL are salvaged from April to June. Smaller larvae are not efficiently captured in the salvage facilities.

The salvage index is routinely used to track and manage incidental take at the SWP and CVP and has also been used to explore factors affecting entrainment and to estimate the effects of the SWP and CVP on Delta fishes. For example, Grimaldo et al. (2009) found that OMR flows and turbidity account for much of the variability in the salvage index for adult delta smelt. In general, salvage increases with increasing net OMR flow reversal (i.e., more negative net OMR flows). Also, delta smelt are generally not salvaged at the south Delta fish facilities when turbidity is less than 10-12 NTU (USFWS 2008). Using salvage data, Kimmerer (2008) calculated that from near 0% to 50 % of the adult smelt population can be entrained at the CVP and SWP during periods of high exports. Although methods to calculate proportional loss estimates have since been debated (Kimmerer 2011, Miller 2011), a number of modeling efforts show that high entrainment losses can adversely affect subsequent smelt generations (Kimmerer 2008, Thompson et al. 2010, Kimmerer 2011, Maunder and Deriso 2011).

It is important to note, however, that salvage underestimates total entrainment losses because there are also major pre-screen losses (Castillo et al. 2012). Studies with Chinook salmon, steelhead, striped bass, and delta smelt have consistently shown that a large fraction (63% to 99.9%) of the entrained fish are not salvaged due to pre-screen losses and capture inefficiencies at the SWP fish facility (Brown et al. 1996, Gingras 1997, Kimmerer 2008, Clark et al. 2009, Castillo et al. 2012). Pre-screen losses are generally attributed to an increased risk of predation and other unfavorable habitat conditions near the SWP and CVP pumps. For juvenile and adult delta smelt, Castillo et al. (2012) found that 94.3% to 99.9% of marked fish released into the SWP Clifton Court Forebay (CCF) were never salvaged and that salvage of marked fish decreased as the distance from the release site to SFPP increased and as residence time in CCF increased.

CCF is a regulating reservoir that temporarily stores water from Old River to improve operations of the SWP pumps. The distance from the radial gates at its entrance to the SFPF at its other end is 4 km. One reason for the large pre-screen losses of delta smelt in CCF may be an increased risk of predation, especially when delta smelt spend a relatively long time in the reservoir in the presence of predators. Particle tracking modeling was used to estimate residence time of weakly swimming delta smelt. In 21-day simulations with the three-dimensional (3-D) hydrodynamic model UnTRIM, MacWilliams and Gross (2013) found that the time particles spend in CCF varies greatly with wind and SWP operating conditions. They estimated transit times for passive particles from the radial gates to the SFPF (e.g. larval delta smelt) of 4.3 days under moderate export conditions (average daily SWP export rate of 2,351 cfs) and 9.1 days under low export conditions (689 cfs). These types of modeling results help inform and understand estimates of pre-screen losses inside CCF as well as in the channels leading to the SWP and CVP water export facilities. The CVP does not have a regulating reservoir in the Delta and CVP prescreen losses in the river channels leading to the TFCF are likely different from SWP prescreen losses, but there are no studies quantifying these differences.

Delta smelt are most vulnerable to entrainment when, as adults, they migrate from brackish water into fresh water, or as larvae, when they move from fresh water into brackish water. While some delta smelt live year-round in fresh water, most rear in the low-salinity regions of the estuary at a relatively safe distance from the SWP and CVP pumps. The timing, direction and geographic extent of the upstream spawning migration of adult delta smelt affects entrainment of adult delta smelt (Sweetnam 1999, Sommer et al. 2011a). The risk of entrainment for fish that migrate into the central and south Delta is highest when outflow is at intermediate levels (~20,000 to 75,000 cfs) and OMR flow is more negative than -5000 cfs (USFWS 2008). In contrast, when adult delta smelt migrate upstream to the Sacramento River and into the Cache Slough region or do not migrate upstream at all, entrainment

1151 risk is appreciably lower. As explained later in this report, adult delta smelt may not move very far
1152 upstream during extreme wet years because the region of low salinity habitat becomes fresh and suitable
1153 for spawning (e.g., Suisun Bay or Napa River).

1154 Transport mechanisms are most relevant to larval fishes, which have little ability to swim or
1155 otherwise affect their location. Dispersal from hatching areas to favorable nursery areas with sufficient
1156 food and low predation, is generally considered one of the most important factors affecting the mortality
1157 of fish larvae (Hjort 1914, Hunter 1980, Anderson 1988, Leggett and Deblois 1994). Smelt larvae of
1158 various species exhibit diverse behaviors to reach and maintain favorable position within estuaries
1159 (Laprise and Dodson 1989, Bennett et al. 2002). Such nursery areas provide increased feeding success,
1160 growth rates and survival (Laprise and Dodson 1989, Sirois and Dodson 2000a, b, Hobbs et al. 2006).
1161 Until recently it was thought that larval delta smelt were transported from upstream hatching areas to
1162 downstream rearing areas, particularly the shallow productive waters of Suisun Bay (Moyle et al. 1992).
1163 Spring distributions of post-larval and small juvenile delta smelt support this view (Dege and Brown
1164 2004). The distributions of these life stages were centered upstream of X2, but approached X2 as fish
1165 aged. These distributions could be displaced, and shifted up or down estuary with outflow and the
1166 shifting position of X2 (Dege and Brown 2004). More recent evidence suggests, however, that the
1167 timing and extent of downstream movement by young delta smelt is more variable than previously
1168 thought (J. Hobbs, U.C. Davis, unpublished data) and that some may remain in upstream areas
1169 throughout the year (Sommer et al. 2011a, Contreras et al. 2011, Merz et al. 2011, Sommer and Mejia
1170 2013).

1171 Adult spawning site selection affects the potential importance of transport and entrainment to
1172 larvae. The risk of larval entrainment appears to increase with proximity to the south Delta export
1173 pumps (Kimmerer and Nobriga 2008). Larvae hatching in the San Joaquin River channel from Big

Break upstream to the city of Stockton can be affected by several interacting processes. Flows from the San Joaquin, Calaveras, Mokelumne and Cosumnes rivers act to cause net downstream flow, whereas export levels at the south Delta pumps act to reverse net flows in the lower San Joaquin River. High export rates can create negative flows past Jersey Point on the lower San Joaquin River (“Qwest,” see Dayflow documentation: <http://www.water.ca.gov/dayflow/output/Output.cfm>) and negative OMR flows (fig. 24) . Tidal conditions can also act in favor of downstream transport or entrainment depending upon whether the Delta is filling or draining (Arthur et al. 1996).

Figure 24. Flows in cubic feet per second for Sacramento River at Rio Vista, San Joaquin River at Vernalis, Qwest (WEST), Old and Middle River, and total exports for 2005, 2006, 2010 and 2011. (Data are from 2013 Dayflow).

Predation Risk

Small planktivorous fishes, including osmerids, serve as prey for larger fishes, birds and mammals. As prey, they have the critically important trophic function of transferring energy from the bottom of the food web to higher trophic levels. Consequently, they are often subjected to intense predation pressure (Gleason and Bengsten 1996, Jung and Houde 2004, Hallfredsson and Pedersen 2009, Nobriga et al. in press). Prey fish populations compensate for high mortality through high reproductive rates, including strategies such as repeat spawning by individuals and rapid maturation (Winemiller and Rose 1992, Rose et al. 2001). Predation is likely the dominant source of mortality for fish larvae, along with starvation and dispersion to inhospitable habitats (Hjort 1914, Hunter 1980, Anderson 1988, Leggett and DeBlois 1994).

Since predation is a natural part of functional aquatic ecosystems, predators are likely not responsible for long-term declines in populations of prey fishes, such as delta smelt, without some additional sources of stress that disrupts the predator-prey relationship (Nobriga et al. in press).

Predation may become an issue when established predator-prey relationships are disrupted by habitat change or species invasions (Kitchell et al. 1994). For example, prey may be more susceptible to predation if they are weakened by disease, contaminants, poor water quality, or starvation. Similarly, the creation of more “ambush habitat” (e.g. structures, weed beds) or the introduction of a novel piscivore also may dramatically shift the existing predator-prey relationships. Virtually all fishes of appropriate size will feed on fish larvae when available and predation is maximal when larvae lengths were 10% of the length of the predator (Paradis et al. 1996). Within the upper estuary during spring juvenile salmonids and Mississippi silversides are known to feed on fish larvae (Bennett and Moyle 1996, Merz 2001, 2002) and are present when and where delta smelt larvae are present.

Recent modeling efforts show that delta smelt declines are negatively associated with metrics assumed to reflect the abundance of predators in the estuary (Maunder and Deriso 2010, Miller 2012); however, there is little empirical evidence to support the idea that delta smelt contributed to the diets of most piscivores in any measurable manner (Nobriga and Feyrer 2007). Even in late 1960’s when smelt were relatively more abundant in the estuary, they were still relatively uncommon in the stomachs of striped bass (Nobriga and Feyrer 2007), except see Stevens (1963). Evaluations of suspected inverse correlations between adult striped bass abundance (older than age 3) estimates and juvenile delta smelt mortality indices (Mac Nally et al. 2010, Thomson et al. 2010, Maunder and Deriso 2011, Miller et al. 2012) did not detect the inverse correlations hypothesized and did not provide evidence of an impact of adult striped bass predation on delta smelt. Larger adult (age 3+) striped bass are less likely to be substantial predators because very small fishes like delta smelt represent a low value (e.g. calories) prey. This does not mean that predation isn’t a primary source of mortality, but that delta smelt are not a major prey item of large striped bass, so predation is relatively difficult to detect.

We suggest that age-1 through about age-3 striped bass are probably a more significant predator of subadult delta smelt than adult striped bass because age 1-3 striped bass are resident in the estuary and thus, acquire the vast majority of their energy from estuarine prey (Stevens 1966, Baxter et al. 2010; Loboschefskey et al. 2012). Juvenile striped bass demand for prey (meaning estimated consumption of all prey types combined) is very closely correlated with abundance (Loboschefskey et al. 2012). Like adult striped bass abundance, juvenile striped bass abundance does not appear to be a predictor of delta smelt survival during summer-fall (fig. 25). Modeling studies indicate that striped bass predation rates on prey are affected by temperature and predator abundance (Loboschefskey et al. 2012). However, prey abundance can be strongly linked to changes in predator abundance or not linked at all depending on the strength of their interaction in the food web (Essington and Hansson 2004). It is not currently known if changes in juvenile striped bass abundance correspond with changes in striped bass' per capita, or population level predation rate on delta smelt.

Figure 25. Correlation of the log of the ratio of the delta smelt fall midwater trawl abundance index (FMWT) to the summer townet abundance index (STN) (an index of summer survival) with log abundance of age 1-3 striped bass.

Largemouth bass and other centrarchids are also a concern because of their increasing abundance (fig 22; Brown and Michniuk 2007), and because of inverse correlations between largemouth bass abundance and delta smelt abundance (Nobriga and Feyrer 2007, Thomson et al. 2010, Maunder and Deriso 2011). These correlations could represent predation on delta smelt by largemouth bass, or the very different responses of the two species to changing habitat within the Delta (Moyle and Bennett 2008). Current data suggest that largemouth bass populations have expanded as the SAV *Egeria densa* has invaded the Delta (Brown and Michniuk 2007). *E. densa* and largemouth bass are particularly prevalent in the central and southern Delta (Brown and Michniuk 2007). However, there is little

evidence that largemouth bass are major consumers of delta smelt due to low spatial co-occurrence (Baxter et al. 2010; Conrad et al., In prep).

As noted above, predation on fish larvae can also be important. Juvenile and small adult fishes of many species will consume fish larvae when they are available, including largemouth bass and bluegill. Bennett and Moyle (1996) and Bennett (2005) noted this and specifically identified Mississippi silversides as potential predators on delta smelt larvae. These authors also documented increases in the silverside population from the mid-1970s through 2002. Consumption of delta smelt by Mississippi silversides in the Delta was recently verified using DNA techniques (Baerwald et al. 2012). Larval predation is discussed in more detail in the next Chapter.

Toxicity and Contaminants

The movement of contaminants through aquatic ecosystems is complex and dynamic, and many contaminants are difficult to detect and expensive to monitor (Scholz et al. 2012). Contaminants are likely an important category of stressors for fishes and other aquatic organisms in many estuaries. Pesticides in particular may be a contributing factor in the decline of delta smelt (NRC 2012). Scholz et al. (2012) give an overview of changing pesticide-use patterns over time in the SFE and elsewhere and their potential effects on delta smelt and ecological resilience. Delta smelt are likely exposed to a variety of contaminants throughout their life cycle but the frequency and magnitude of the effects of contaminants on delta smelt health and reproduction and that of other species are not very well understood in the SFE (Johnson et al. 2010, Brooks et al. 2012). Exposures seem most likely for adult delta smelt during the contaminant first flush, when initial rainstorms wash accumulated contaminants from the lands surface into waterways (Kuivila and Foe 1995); however, adult fish are the life stage most resistant to contaminants. Kuivila and Moon (2004) found that peak densities of larval and juvenile delta smelt sometimes coincided in time and space with elevated concentrations of dissolved

pesticides in the spring. These periods of co-occurrence lasted for up to 2–3 weeks, but concentrations of individual pesticides were low and much less than would be expected to cause acute mortality. Despite several large studies of the possible role of contaminants in the decline of POD fishes, including delta smelt, there was little evidence for acute effects of pesticides on fish or invertebrates (Werner et al. 2008, Werner et al. 2010a, Werner et al. 2010b). Brooks et al. (2012) concluded that chronic, sublethal effects on fish health were the more likely outcome of contaminant exposure in SFE. Current work is underway to examine the health and condition of adult delta smelt; this work will shed light on possible contaminant exposure but it may not reveal the extent to which such exposure compromises reproduction potential or affects survival.

Another avenue for indirect contaminant effects is through trophic pathways. Herbicides can affect primary producers, and insecticides can affect invertebrate prey species (e.g., Brander et al. 2009, Weston et al. 2012). Excessive nutrient discharges (e.g. ammonium) may also have effects on trophic processes (e.g., ammonium). These food-mediated effects of contaminants are discussed in the next section.

Food and Feeding

The presence of food is, obviously, a critical habitat attribute for any organism; however, the factors determining the quantity and quality of available food can be quite complex. In this section, we begin with a brief review of information about trophic processes in the upper SFE. We then discuss the available data on prey consumed by delta smelt. Finally, we provide a review of information on factors possibly affecting abundance and quality of food organisms. In the life stage CMs (figs. 9-12), the food habitat attribute is expressed in several ways. In general, food availability simply refers to quantity of appropriate foods. In the adult to larvae model and larvae to juvenile model, prey visibility is highlighted because of the previously described relationship between suspended particles and successful

feeding by larval delta smelt. In the juvenile life stage model prey quality is mentioned in relation to the presence or absence of preferred prey items and possible effects of HABs on preferred prey.

Estuaries are commonly characterized as highly productive nursery areas for a suite of organisms. Productivity of estuarine ecosystems is broadly believed to be fueled by detritus-based food webs. In the SFE, much of the community metabolism in pelagic waters does result from microbial consumption of organic detritus. However, evidence suggests that metazoan production in pelagic waters is primarily driven by phytoplankton production (Sobczak et al. 2002, 2005, Mueller-Solger et al. 2002, 2006, Kimmerer et al. 2005). Protists (flagellates and ciliates) consume both microbial and phytoplankton prey (Murrell and Hollibaugh 1998, York et al. 2010) and are an additional important food source for many copepod species in the estuary (Rollwagen-Bollens and Penry 2003, Bouley and Kimmerer 2006, Gifford et al. 2007, MacManus et al. 2008). However, the conversion of dissolved and particulate organic matter to microbial biomass and then to zooplankton is a relatively slow and inefficient process. Thus, shifts in phytoplankton and microbial food resources for zooplankton might favor different zooplankton species. Moreover, phytoplankton production and biomass in the SFE is low compared to many other estuaries (e.g., Jassby et al. 2002, Kimmerer et al. 2005, Wilkerson et al. 2006, Cloern and Jassby 2012). The recognition that phytoplankton production might impose limits on pelagic fishes, such as delta smelt, through food availability has led to intense interest in factors affecting phytoplankton production and species composition and in management actions aimed at enhancing high-quality phytoplankton production. In addition, there is a major need to understand other trophic pathways given the observation that larger delta smelt periodically can take advantage of epibenthic prey (see below).

Phytoplankton biomass (measured as chlorophyll-*a*) has been routinely monitored in the estuary since the 1970s. The 1975-2012 median chlorophyll-*a* concentration across all IEP EMP stations is 2.8

µg/L (n=13482, interquartile range (IQR)=5 µg/L). Seasonally, the highest chlorophyll-*a* concentrations tend to be observed in May and June and the lowest concentrations in December and January. Regionally, monitoring stations in the South Delta/San Joaquin River usually have the highest chlorophyll-*a* concentrations.. There has been a well-documented long-term decline in phytoplankton biomass (chlorophyll-*a*) and primary productivity (estimated from measurements of chlorophyll-*a* and of water column light utilization efficiency) to very low levels in the Suisun Bay region and the lower Delta (Jassby et al. 2002). Jassby et al. (2002) detected a 47% decline in June–November chlorophyll-*a* and a 36% decline in June–November primary production between the periods 1975–1985 and 1986–1995. Jassby (2008) updated the phytoplankton analysis to include the more recent data (1996–2005) from the Delta and Suisun Bay. Jassby (2008) confirmed a long-term decline in chlorophyll-*a* from 1975 to 2005 but also found that March–September chlorophyll-*a* had an increasing trend in the Delta from 1996 to 2005. Suisun Bay did not exhibit any trend during 1996–2005. A similar pattern was noted for primary production in the Delta. These chlorophyll-*a* patterns continued to hold through 2008 according to a more recent study by Winder and Jassby (2011). In the most recent decade (2003–2012), the median chlorophyll-*a* concentration across all IEP EMP stations was 2 ug/L (n= 2620, IQR=2 ug/L), compared to the 1975–2002 median chlorophyll-*a* concentration of 3 ug/L (n= 10862, IQR=6 ug/L) (fig. 26). Most of the decrease was due to declines during May–October and especially the near-elimination of the formerly common “spring bloom” of phytoplankton in May (fig. 26). In summary, phytoplankton biomass and production in the Delta and Suisun Bay seem to have reached a low point by the end of the 1987–1994 drought. While they recovered somewhat in the Delta, chlorophyll-*a* stayed consistently low in Suisun Bay through the POD years.

Figure 26. Interquartile ranges (boxes) and medians (lines) for chlorophyll *a* measured monthly at all IEP EMP stations from 1975–2002 (blue) and 2003–2012 (red). Data from <http://www.water.ca.gov/bdma/>.

A major reason for the long-term phytoplankton reduction in the upper SFE after 1985 is benthic grazing by the invasive overbite clam (*Potamocorbula amurensis* also known as *Corbula amurensis*) (Alpine and Cloern 1992), which became abundant by the late 1980s (Kimmerer 2002). The overbite clam was first reported from San Francisco Estuary in 1986 and it was well established by 1987 (Carlton et al. 1990). Prior to the overbite clam invasion, there were periods of relatively low clam biomass in the upper SFE because the invasive Asiatic freshwater clam (*Corbicula fluminea*) (introduced in the 1940s) colonized Suisun Bay during high flow periods and the estuarine clam *Mya arenaria* (also known as *Macoma balthica*, an earlier introduction) colonized Suisun Bay during prolonged (> 14 month) low flow periods (Nichols et al. 1990). Thus, there were periods of relatively low clam grazing rates while one species was dying back and the other was colonizing, resulting in neither reaching high abundances. The *P. amurensis* invasion changed this formerly dynamic clam assemblage because *P. amurensis*, which is tolerant of a wide range of salinity, can maintain large, permanent populations in the brackish water regions of the estuary. *P. amurensis* biomass and grazing usually increase from spring to fall which contributes to the reduction in phytoplankton biomass from May to October relative to historical levels. In addition, the grazing influence of *P. amurensis* extends into the freshwater Delta (Kimmerer and Orsi 1996, Jassby et al. 2002) beyond the clam's typical brackish salinity range, presumably due to tidal dispersion of phytoplankton-depleted water between regions of brackish water and fresh water.

Shifts in nutrient concentrations and ratios may also contribute to the phytoplankton reduction and changes in algal species composition in the SFE. Phytoplankton production in the San Francisco Estuary is generally light limited with nutrient concentrations exceeding concentrations limiting primary production. Ammonium concentrations in the Delta and Suisun Bay have significantly increased over the last few decades, due largely to increased loading from the Sacramento Regional Water Treatment

Plant (SRWTP) (Jassby 2008). Dugdale et al. (2007) and Wilkerson et al. (2006) found that high ammonium concentrations prevented the formation of diatom blooms but stimulated flagellate blooms in the lower estuary. This occurs because diatoms preferentially utilize ammonium in their physiological processes even though it is used less efficiently. Thus, diatom populations must consume available ammonium before nitrate, which supports higher growth rates, can be utilized. Glibert (2012) analyzed long-term data (from 1975 or 1979 to 2006 depending on the variable considered) from the Delta and Suisun Bay and related changing forms and ratios of nutrients, particularly changes in ammonium, to declines in diatoms and increases in flagellates and cyanobacteria. Similar shifts in species composition were noted by Brown (2009). More recently, Parker et al. (2012) found that the region where blooms are suppressed extends upstream into the Sacramento River to the SRWTP, the source of the majority of the ammonium in the river (Jassby 2008). Parker et al. (2012) found that at high ambient ammonium concentrations, river phytoplankton cannot efficiently take up any form of nitrogen including ammonium, leading to often extremely low biomass in the river. A study using multiple stable isotope tracers (C. Kendall, USGS, personal communication) found that the cyanobacteria *M. aeruginosa* utilized ammonium, not nitrate, as the primary source of nitrogen in the central and western Delta. The SRWTP reduced its discharge by 12% starting in May 2009 (S. Dean, Sacramento Regional County Sanitation District, personal communication). This reduction likely contributed to the relatively low ambient Sacramento River ammonium concentrations observed in spring 2010 and may have led to subsequent unusually strong spring diatom blooms in Suisun Bay (Dugdale et al. 2013).

Jassby (2008) suggested the following comprehensive explanation for his observations. Phytoplankton production in the lower Delta is associated with flow and residence time; however, other factors introduce a substantial degree of interannual variability. Benthic grazing by *C. fluminea* is likely a major factor (Lucas et al. 2002, Lopez et al. 2006) but current data are inadequate to estimated the

magnitude of this effect. In Suisun Bay, benthic grazing by *P. amurensis* is a controlling factor that keeps phytoplankton at low levels. Thus, metazoan populations in Suisun Bay are dependent on importation of phytoplankton production from the upstream portions of the Delta. Ammonium concentrations and water clarity have increased; however, these two factors should have opposing effects on phytoplankton production. These factors likely also contribute to variability in the interannual pattern but the relative importance of each is unknown. The interactions among primary production, grazing, and transport time can be complex (Lucas et al. 2002, 2009a,b, Lucas and Thompson 2012).

The changes in phytoplankton production and invasion and establishment of the overbite clam *P. amurensis* were also accompanied by a series of major changes in consumers. Many of these changes likely negatively influenced pelagic fish production, including delta smelt. The quantity of food available to delta smelt is a function of several factors, including but not limited to seasonal trends in abundance and species specific salinity tolerances influencing distribution (Kimmerer and Orsi 1996, Hennessy and Enderlein 2013). Seasonal peaks in abundance vary among calanoid copepods consumed as prey by delta smelt, *E. affinis* in April-May (fig. 27), *P. forbesi* in July (fig 28), and *A. sinensis* in Sep-Oct (fig. 29). Upstream, the calanoid copepod *S. doerrii* is most abundant May-June (fig. 30). The seasonal trend in cladocerans (fig. 31) and mysid (fig. 32) prey are similar, being most abundant in summer.

Figure 27. Density (number/m³) of adult *Eurytemora affinis* by month for three salinity ranges. Data from the IEP Zooplankton Study index stations (n=16).

Figure 28. Density (number/m³) of adult *Psuedodiaptomus forbesi* by month for three salinity ranges. Data from the IEP Zooplankton Study index stations (n=16).

1402 **Figure 29.** Density (number/m³) of adult *Acartiella sinensis* by month. Data from the IEP Zooplankton Study index
1403 stations (n=16).

1404 **Figure 30.** Density (number/m³) of adult *Sinocalanus doerrii* by month. Data from the IEP Zooplankton Study
1405 index stations (n=16).

1406 **Figure 31.** Density (number/m³) of all cladoceran taxa by month. Data from the IEP Zooplankton Study index
1407 stations (n=16).

1408 **Figure 32.** Density (number/m³) of all mysid shrimp taxa by month. Data from the IEP Zooplankton Study index
1409 stations (n=16).

1410 Larval delta smelt March through June rely heavily on first juvenile, then adult stages of the
1411 calanoid copepods *Eurytemora affinis* and *Pseudodiaptomus forbesi*, as well as cladocerans (Nobriga
1412 2002, Hobbs et al. 2006, Slater and Baxter submitted), and *Sinocalanus doerrii* (fig. 33). Regional
1413 differences in food use occur, with *E. affinis* and *P. forbesi* being major prey items downstream in the
1414 LSZ with a transition to increasing use of *S. doerrii* and cyclopoid copepods as food upstream into the
1415 CS-SRDWSC (fig. 33). Juvenile delta smelt (June-September) rely extensively on calanoid copepods
1416 such as *E. affinis* and *P. forbesi*, especially in freshwater (<1 and Cache Slough-Sacramento River
1417 Deepwater Ship Channel (CS-SRDWSC)) but there is great variability among regions (figs. 34-37).
1418 Larger fish are also able to take advantage of mysids, cladocerans, and gammarid amphipods (Moyle et
1419 al. 1992, Lott 1998; Feyrer et al. 2003, Steven Slater, California Department of Fish and Wildlife,
1420 unpublished data) (figs. 34-37). The presence of several epi-benthic species in diets therefore indicates
1421 that food sources for this species are not confined to pelagic pathways. Such food sources may be
1422 especially important in regions of the estuary where there is extensive shoal habitat such as Liberty
1423 Island (Steven Slater, California Department of Fish and Wildlife, unpublished data) . Subadult delta

smelt (September through December) prey items are very similar to those of juvenile delta smelt but with increased variability in diet composition (Moyle et al. 1992, Lott 1998, Steven Slater, California Department of Fish and Wildlife, unpublished data) (figs. 34-37) coinciding with the seasonal decline in pelagic zooplankton, such as *P. forbesi* (fig. 28) and mysids (fig. 32). Food habits of adult delta smelt during the winter and spring (January-May) have been less well documented (Moyle et al. 1992). In 2012, diet of adults in the LSZ and <1 ppt were found to include cyclopoid copepods, other than *Limnoithona* spp., with a mix of larger prey types, amphipods, cladocerans, cumaceans, and larval fish and in CS-SRDWSC the calanoid copepod *S. doerrii* continued to be a large portion of the diet (Steven Slater, California Department of Fish and Wildlife, unpublished data)(fig. 38). Larval fish found in stomachs of delta smelt in the higher salinity areas were primarily Pacific herring (*Clupea pallasii*), with some longfin smelt, and prickly sculpin (*Cottus asper*) in the Sacramento River and CS-SRDWSC region; no delta smelt larvae were found in the stomachs of adults (Steven Slater, California Department of Fish and Wildlife, unpublished data).

Figure 33. Diet by percent weight of larval delta smelt (<20 mm FL) at various salinities (<6, 1-6, and <1 ppt) and in the Cache Slough-Sacramento River Deepwater Ship Channel (CS-SRDWSC) during 2005, 2006, 2010, and 2011.

Figure 34. Diet by percent weight of age-0 delta smelt collected April through December at >6 ppt in 2005, 2006, 2010, and 2011.

Figure 35. Diet by percent weight of age-0 delta smelt collected April through December at 1-6 ppt in 2005, 2006, 2010, and 2011.

Figure 36. Diet by percent weight of age-0 delta smelt collected April through December at <1 ppt in 2005, 2006, 2010, and 2011.

1446 **Figure 37.** Diet by percent weight of age-0 delta smelt collected April through December in Cache Slough-
1447 Sacramento River Deepwater Ship Channel (CS-SRDWSC) in 2005, 2006, 2010, and 2011.

1448 **Figure 38.** Diet by percent weight of age-1 delta smelt collected January through May 2012 at various salinities (1-
1449 6 and <1 ppt) and in the Cache Slough-Sacramento River Deepwater Ship Channel (CS-SRDWSC).

1450 The large proportion of benthic amphipods, cumaceans, and some cladocerans (*Camptocercus*
1451 spp.) in the diet is a notable change from delta smelt in the 1970s. Delta smelt diets historically did
1452 include amphipods, notably *Corophium* spp. (Moyle et al. 1992), yet it was a small fraction of a mostly
1453 pelagic based diet. The considerable use of benthic invertebrates for food in recent years is believed in
1454 large part due to food limitation associated with the long-term decline and changes in composition of the
1455 pelagic food web (Slater and Baxter submitted). The quality of benthic invertebrates as food is not
1456 currently understood, yet amphipods are lower in energy (calories per gram) than copepods (Cummins
1457 and Wuychek 1971, Davis 1993) and mysids (Davis 1993).

1458 As noted previously, the changes in phytoplankton production and phytoplankton species
1459 abundances observed and the invasion of *P. amurensis* may have had important consequences for
1460 consumer species preyed upon by delta smelt. For example, a major step-decline was observed in the
1461 abundance of the copepod *E. affinis* possibly due to predation by the overbite clam (Kimmerer et al.
1462 1994) or indirect effects on copepod food supply. Predation by *P. amurensis* may also have been
1463 important for other zooplankton species (Kimmerer 2008). Northern anchovy *Engraulis mordax*
1464 abandoned the low salinity zone coincident with the *P. amurensis* invasion, presumably because the
1465 clam reduced planktonic food abundance to the point that occupation of the low-salinity waters was no
1466 longer energetically efficient for this marine fish (Kimmerer 2006). Similarly, longfin smelt *Spirinchus*
1467 *thaleichthys* shifted its distribution toward higher salinity in the early 1990s, also presumably because of
1468 reduced pelagic food in the upper estuary (Fish et al. 2009). There was also a major step-decline in

mysid shrimp in 1987–1988, likely due to competition with the overbite clam for phytoplankton (Orsi and Mecum 1996). Mysid shrimp had been an extremely important food item for larger fishes like longfin smelt and juvenile striped bass (Orsi and Mecum 1996), and may be consumed by larger delta smelt (Moyle et al. 1992). The decline in mysids was associated with substantial changes in the diet composition of these and other fishes, including delta smelt (Feyrer et al. 2003, Bryant and Arnold 2007). As described above, the population responses of longfin smelt and juvenile striped bass to winter–spring outflows changed after the *P. amurensis* invasion. Longfin smelt relative abundance was lower per unit outflow after the overbite clam became established (Kimmerer 2002b). Age-0 striped bass relative abundance stopped responding to outflow altogether (Sommer et al. 2007). One hypothesis to explain these changes in fish population dynamics is that lower prey abundance reduced the system carrying capacity (Kimmerer et al. 2000, Sommer et al. 2007).

In addition to a long-term decline in calanoid copepods and mysids in the upper Estuary, there have been numerous copepod species introductions (Winder and Jassby 2011). *P. forbesi*, a calanoid copepod that was first observed in the estuary in the late 1980s, has replaced *E. affinis* as the most common delta smelt prey during the summer. It may have a competitive advantage over *E. affinis* due to its more selective feeding ability. Selective feeding may allow *P. forbesi* to utilize the remaining high-quality algae in the system while avoiding increasingly more prevalent low-quality and potentially toxic food items such as *M. aeruginosa* (Mueller-Solger et al. 2006, Ger et al. 2010a). After an initial rapid increase in abundance, *P. forbesi* declined somewhat in abundance from the early 1990s in the Suisun Bay and Suisun Marsh region but maintained its abundance, with some variability, in the central and southern Delta (Winder and Jassby 2011). Although substantial uncertainties about mechanisms remain, the decline of *P. forbesi* in the Suisun region may be related to increasing recruitment failure and mortality in this region due to competition and predation by *P. amurensis*, contaminant exposures,

and entrainment of source populations in the Delta (Mueller-Solger et al. 2006, Winder and Jassby 2011, Durand 2010).

The abundance of a more recent invader, the cyclopoid copepod *Limnoithona tetraspina*, significantly increased in the Suisun Bay region beginning in the mid-1990s. It is now the most abundant copepod species in the Suisun Bay and confluence region of the estuary (Bouley and Kimmerer 2006, Winder and Jassby 2011). Gould and Kimmerer (2010) found that it grows slowly and has low fecundity. Based on these findings they concluded that the population success of *L. tetraspina* must be due to low mortality and that this small copepod may be able to avoid visual predation to which larger copepods are more susceptible. It has been hypothesized that *L. tetraspina* is an inferior food for pelagic fishes including delta smelt because of its small size, generally sedentary behavior, and ability to detect and avoid predators (Bouley and Kimmerer 2006, Gould and Kimmerer 2010). Nevertheless, this copepod has been found in the guts of delta smelt when *Limnoithona* spp. occurs at extremely high densities relative to other zooplankton (Slater and Baxter submitted). Recent experimental studies addressing this issue suggest that larval delta smelt will consume and grow on *L. tetraspina*, but growth is slower than with *P. forbesi* (Kimmerer et al. 2011). It remains unclear if consuming this small prey is energetically beneficial for delta smelt at all sizes or if there is a breakpoint above which larger delta smelt receive little benefit from such prey. *Acartiella sinensis*, a calanoid copepod species that invaded at the same time as *L. tetraspina*, also reached considerable densities in Suisun Bay and the western Delta over the last decade (Hennessy 2010), although its suitability as food for pelagic fish species remains unclear.

Preliminary information from studies on pelagic fish growth, condition, and histology provide additional evidence for food limitation in pelagic fishes in the estuary (IEP 2005). In 1999 and 2004, delta smelt growth was low from the Sacramento-San Joaquin confluence through Suisun Bay relative

to other parts of the system. Delta smelt collected in 2005 from the Sacramento-San Joaquin confluence and Suisun Bay also had high incidence of liver glycogen depletion, a possible indicator of food limitation (Bennett et al. 2008). As previously noted, warm water temperatures during the summer period may have exacerbated lack of food by raising metabolic rate of delta smelt. Based on data for histopathology, date of birth from otoliths, and growth rates from otoliths of delta smelt in 2005, Bennett et al. (2008) proposed a novel strategy for delta smelt survival in 2005. Natural selection appeared to favor individuals with a specific set of characters, including relatively slow larval development, but faster than average juvenile growth in July. Water temperatures in July typically include the annual maximum. The salinity field can also change rapidly as freshwater flow out of the Delta changes (fig. 17). Many of these fish surviving into the pre-adult stage had also hatched earlier in the spawning season (i.e. before May).

For many fishes, success at first feeding is believed to be critical to larval survival and a major cause of year-class variability (e.g ‘critical period hypothesis’, Hjort 1914, Leggett and DeBlois 1994). In rainbow smelt *Osmerus mordax* a related smelt species, calculated larva mortality rates were related to feeding conditions at first feeding that varied on a predictable cycle of 15 days associated with tide and photoperiod (Sirois and Dodson 2000b). In feeding experiments, copepod evasion behavior affected capture by larval striped bass, and *E. affinis* was among the more easily captured species (Meng and Orsi 1991). There has been a long-term decline in calanoid copepods in the upper estuary, particularly in the Suisun Region (Winder and Jassby 2011), potentially reducing feeding success, growth and thereby survival. Currently, *E. affinis* abundance peaks in spring (Hennessy 2010, 2011) coincident with hatching of delta smelt. *E. affinis* abundance has been negatively related to X2 since the clam invasion (Kimmerer 2002). When X2 is “high” outflow is low and *E. affinis* densities are low.

These lines of evidence suggest that the first feeding conditions may improve in springs with higher outflow.

Changes in the quality and quantity of available prey may have contributed to the observed reduction in the mean size of delta smelt in fall since the early 1990s (Sweetnam 1999, Bennett 2005). The importance of food resources as a driver is supported by Kimmerer (2008), who showed that delta smelt survival from summer to fall is correlated with biomass of copepods in the core range of delta smelt. Other variations of this correlation were shown by Maunder and Deriso (2011) and Miller et al. (2012). Miller et al. (2012) have tested for an explicit influence of prey density during the fall. Miller et al. (2012) found a stronger correlation between delta smelt abundance during the fall and prey density during the fall than for prey density during the summer.

Harmful algal blooms

Periodic blooms of the toxic blue-green alga *Microcystis aeruginosa* during late summer, most commonly August and September are an emerging concern for delta smelt (Lehman et al. 2005). Although this HAB typically occurs in the San Joaquin River away from the core summer distribution of delta smelt, some overlap is apparent during blooms and as cells and toxins are dispersed downstream after blooms (Baxter et al. 2010). Density rankings of *Microcystis* at STN stations were highest in the south Delta, east Delta and Lower San Joaquin regions; yet *Microcystis* distribution may be expanding north over time (Morris in press). Moreover, studies by Lehman et al. (2010) suggest that delta smelt likely are exposed to microcystins, which may degrade their habitat and perhaps affect the distribution of delta smelt (Baxter et al. 2010). For example, these HABs are known to be toxic to another native fish of the region, Sacramento splittail *Pogonichthys macrolepidotus* (Acuna et al. 2012a) and the alien threadfin shad (Acuna et al. 2012b). Histopathology evidence from Lehman et al. (2010) suggested the

health of two common fish in the estuary, striped bass, and Mississippi silversides (*Menidia audens*), was worse at locations where microcystin concentrations were elevated.

Indirect effects are also likely as *Microcystis* blooms are toxic copepods that serve as to the primary food resources of delta smelt (Ger et al. 2009; 2010a,b). Ger et al. (2009) determined toxicity of one form of microcystin (LR) to two species of calanoid copepods, *E. affinis* and *P. forbesi*, which are important as food to delta smelt. They found that, although the copepods tested were relatively sensitive to microcystin-LR compared to other types of zooplankton, ambient concentrations in the Delta were unlikely to be acutely toxic. However, chronic effects were not determined and Lehman et al. (2010) found that *Microcystis* may indeed contribute to changes in phytoplankton, zooplankton and fish populations in the Delta. Factors that are thought to cause more intensive *Microcystis* blooms include warmer temperatures, lower flows, high nitrogen levels, and relatively clear water (Lehman et al. 2005, Baxter et al. 2010, Morris in press).

Chapter 5: Delta Smelt Responses

Population Biology

This section is included to introduce general concepts in population biology that are utilized in the following sections of this Chapter and to generally describe delta smelt population dynamics. Explaining these concepts and population trends at the beginning is intended to reduce repetitive text in the remaining sections and to reduce possible confusion for readers unfamiliar with the concepts. The concepts are discussed specifically in the context of delta smelt.

Relationships between numbers of spawning fish or other measures of potential spawning stock (e.g., numbers of subadult or mature prespawning fish) and the numbers of fish of a given age or life stage in the subsequent generation are known as a stock-recruitment relationship. Stock-recruitment

relationships have been described for many species and are a central part of the management of commercially and recreationally fished species (Myers et al. 1995, Touzeau and Gouze 1998). Different forms of stock-recruitment relationships are possible, including density-independent, density-dependent, and density-vague types. The density-independent type occurs when the current size of the population has no effect on population growth. This type of population growth is rare in fish populations but might occur during the initial invasion of a predator species that native prey fishes are unable to evade. Rapid population growth would occur but only until the food source was depleted. Density dependence occurs when the current population size affects population growth. This is common in many fish populations. Extending the previous example, if a fish population outgrows its food supply, individual fish will starve and die until the remaining food resources are sufficient to support the survivors. Thus, the survival of the population depends on its density. In reality there is often a mixture of responses with density independent population growth occurring when the population is small, if resources are abundant, and density dependent growth occurring as the population becomes large and resources are become limiting. This idea of density dependence in relation to resource limitation is related to the idea of carrying capacity. The carrying capacity of an ecosystem is the number of individuals of all species that can be supported by the available resources. In reality it can be very difficult to apply this idea to a single species in an ecosystem because of the complex relationships among species and the seasonal, annual, and other changes in resource availability. The density vague type of population growth refers to situations where there is not a statistically demonstrable stock-recruitment relationship observable in available data.

In density-dependent stock-recruitment relationships, the factors causing the density dependence can operate at various points in the life cycle of the new generation. For example, if a large spawning stock produced a large number of eggs and larvae, density dependence could occur at the

larval stage if many of the larvae starved because of insufficient food supplies. Alternatively, if resources were sufficient for larvae and juvenile fish to survive in large numbers, the surviving subadults might overwhelm adult food sources, resulting in low survival and poor reproductive output. Thus, it is important to understand species ecology and survival between life stages to understand how density dependence is affecting a population. Density-independence is more straightforward. In this case, the population is controlled by factors, unrelated to the density of the population. For example, high water temperatures will affect individual fish, whether the population is large or small. In reality populations can be affected by both density-dependent and density-independent factors at different times. Again, it is essential to understand the ecology of the species and survival between life stages to understand the relative important of density dependent and density dependent factors.

Unfortunately, delta smelt were never of sufficient interest as commercial or recreational species to warrant development of stock-recruitment models until they were listed. Data now used to develop stock-recruitment type models for delta smelt started becoming available after the initiation of fisheries studies and monitoring surveys in the late 1950s (1959: TNS; 1967: FMWT) in association with the planning and operation of the CVP and SWP. Note that we deliberately use the phrase “stock-recruitment type models” because classical stock-recruitment models in fisheries management are based on (and produce) estimates of the actual population size of a species as either numbers or biomass. With the exception of Petersen tag estimates for striped bass and sturgeon, IEP fish monitoring surveys were not designed to produce actual population estimates. Instead, they were intended to provide information on trends based on relative abundance indices or catch-per-unit-effort (CPUE, e.g., number per trawl). Moreover, none of the early IEP fish monitoring surveys (TNS, FMWT) were specifically designed to monitor delta smelt, but instead targeted primarily commercially and recreationally more important species such as striped bass..

In any form of a stock-recruitment model, there is a point at which low adult stock will result in low juvenile abundance and subsequent low recruitment to future adult stocks. This can occur even under favorable environmental conditions while the stock “rebuilds” itself. From a stock-recruitment perspective, the recent low abundance of delta smelt is of particular concern. Since about 2002, the current population is smaller than at any time previously in the record, with the exception of the 2011 year class (fig.3).

In the absence of population estimates, delta smelt population biology has been explored using the available abundance indices. Relationships between abundance indices from the current and preceding years can be used as a form of stock-recruitment relationship. Ratios of abundance indices within the same year can be used as indicators of survival between life stages. The two stock-recruitment relations based on the longest data records include the relationship of the FMWT abundance index with the FMWT abundance index in the previous year and the relationship of the TNS abundance index with the FMWT abundance index in the previous year (fig. 39). Because of the large changes that have occurred in the Delta ecosystem, including the invasion by *P. amurensis* and the POD, these plots can be difficult to interpret. It does appear that there is much more variability associated with the FMWT relationship compared to the TNS relationship. This might indicate variable survival between the juvenile and sub adult life stage.

Figure 39. Scatterplots and LOWESS splines depicting the relationship of the Fall Midwater Trawl index of delta smelt relative abundance (FMWT) (1968-2012) and Summer Townet Survey (TNS) (1969-2012) with the the FMWT in the previous year.

Stage-to-stage survival has been explored using ratios of delta smelt abundance indices (fig. 40). The ratio of the TNS to 20 mm Survey gives a relative indicator of survival from larvae to juveniles. The ratio of the FMWT to TNS gives a relative indicator of survival from juveniles to subadults. The

ratio of the SKT to FMWT in the previous year gives a relative indicator of survival from subadults to adults. As for the stock-recruitment relationships these survival indices should be interpreted with caution given the large changes that have taken place in the Delta. The main utility of these indices is identifying years with relatively high or low survival for a specific life stage transition or life stage transitions with differences in annual variability.

Figure 40. Stage to stage survival indices based on data from Summer Townet Survey (TNS), Fall Midwater Trawl (FMWT), and Spring Kodiak Trawl (SKT).

We can standardize the scales of the different survival indices to facilitate comparison of patterns within and among the indices (fig. 41; standardization method explained in caption) The trajectories of adult to larva recruitment and subsequent stage-to-stage survivals for the decade after the onset of the POD (2003-12) are shown in Figure 41 and provide the basis for some additional observations. Note that index values are only meaningful in a relative, not in an absolute sense, and rescaling them does not change the relative relationships among the values in each time series.

Figure 41. Delta smelt recruitment and survival indices based on the annual adult, larval, juvenile, and subadult abundance indices provided by the Spring Kodiak Trawl (adults), 20-mm Survey (larvae), Summer Townet Survey (juveniles), and Fall Miwater Trawl (subadults). Each abundance index was rescaled to a standard range of 1-10 to facilitate comparisons. Larval recruitment (larva/prior adults) and cohort survival indices (all other ratios) were calculated by dividing the rescaled annual indices for one life stage by the rescaled annual indices of the prior life stage or, for larval recruitment, the prior adult stock, thus producing “delta smelt index ratios” shown in the graph. Also shown on the X-axis are water year type for the Sacramento and San Joaquin Valleys.

First, interannual variability in these stock and survival indices declines from larval recruitment (coefficient of variation (CV): 92%), to subsequent larvae to juvenile survival (CV: 67%), juvenile to subadult survival (CV: 43%), to subadult to adult survival (CV: 38%). This result is consistent with expected highly dynamic patterns of recruitment and survival for an annual opportunistic species such as delta smelt. The pattern of reduced variability in survival for larger fish suggests that older fish may no longer be vulnerable to some forms of mortality affecting juveniles either because a factor is no longer important when larger fish are present (e.g., effect of summer high water temperatures on juveniles) or that larger fish escape some forms of mortality (e.g., larger fish are no longer eaten by predators able to consume larvae).

Second, the adult to larvae recruitment suggests: (1) even a small adult delta smelt stock can produce a large number of larvae under the right habitat conditions; but (2) larval recruitment is not a good predictor of juvenile survival and subsequent adult stock size (fig. 41).

Third, there are clear contrasts in delta smelt responses between the two study years 2006 and 2011 (the years of particular interest in this report) (fig. 41). Recruitment and survival were overall greatest in the two wet years 2006 and 2011 (total height of the bars) compared to the other, drier years in the time series, but in 2006 very strong adult to larvae recruitment was followed by very poor larvae to juvenile survival in the summer. Survival from larvae to juveniles was much better in 2011. The poor larvae to juvenile survival in 2006 was associated with subsequent relatively low adult numbers in 2007 (fig. 42). Poor larval recruitment occurred from 2007-2010 a period of very low “POD” abundance indices. In contrast, relatively good stage-to-stage survivals throughout the year in 2011 (fig. 41) was associated with the highest POD index of adult abundance in 2012 (fig. 42). The return to more average “POD level” abundance indices for the delta smelt generation born in 2012 started with relatively poor

adult to larval recruitment which was followed by poor survival indices in the summer and fall (fig. 41).

Figure 42. Annual adult, larval, juvenile, and subadult abundance indices provided by the Spring Kodiak Trawl (adults), 20-mm Survey (larvae), Summer Townet Survey (juveniles), and Fall Miwater Trawl (subadults). Each abundance index was rescaled to a standard range of 1-10 to facilitate comparisons.. Also shown on the X-axis are water year type for the Sacramento and San Joaquin Valleys.

Finally, wetter years appear to coincide with years of higher adult to larvae recruitment, but not of higher stage-to-stage survival indices (fig. 41). On a more quantitative basis, there was a strong positive relationship between adult to larvae recruitment and the summed “water year indices” for the Sacramento and San Joaquin basins (fig. 43; $n=10$, $r^2=0.92$, $P<0.0001$), but no relationships with stage-to-stage survival indices. The water year indices indicate unimpaired hydrological conditions in the two basins. While this relationship is provocative, it is important to note that delta smelt do not directly experience the overall basin hydrology reflected in the water year indices. Instead, as shown in our conceptual model and explained in Chapter 4 and further explored in the life stage sections below, hydrology is an environmental driver that interacts with other drivers to produce the Delta habitat conditions actually experienced by delta smelt. However, it may be an important driver influencing habitat conditions for larval recruitment of delta smelt. Further analyses with in-Delta hydrological conditions are needed to further explore this idea.

Figure 43. Adult to larvae recruitment and stage-to-stage survival indices (fig. 41) plotted against summed Sacramento and San Joaquin Valley Water Year Indices (see <http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST>). The linear regression denotes the relationship between the summed water year indices and adult to larvae recruitment (larvae/prior adults index ratio).

The combined effects of stock-recruitment and stage-to-stage survival indices are somewhat complicated to assess without a proper life cycle model. However, the change in the long-term relationship in summer to fall survival (fig. 61) suggests that the primary factors affecting juvenile survival recently changed and shifted to earlier in the life cycle; however, this would not necessarily affect the stock-recruitment relationship. It would only affect survival from juvenile to subadult. In other words, an individual adult delta smelt might still produce the same number of young; however, fewer young survive to reproduce as adults and fewer adults would produce young. While stock recovery may be possible fairly rapidly via high larval recruitment followed by good survival (fig. 41) recovery of genetic diversity is a much slower process which is an important conservation concern (Fisch et al. 2012).

In addition, the fecundity of adult smelt has likely changed. The mean size of adult delta smelt has declined since the early 1990s (Sweetnam 1999), possibly due to changes in the food web (see Chapter 4). An additional hypothesis is that in some recent years, there may have been selection for smaller, late-spawned larvae as a result of export pumping schedules (Bennett 2011). In particular, high export pumping in late winter may have resulted in high entrainment mortality of offspring from larger, fitter, early spawning females. Curtailment of export pumping in mid-April related to the Vernalis Adaptive Management Program (VAMP), allowed for greater survival of late-spawned, smaller larvae (Bennett et al. 2008, Bennett 2011). The major concern is that these smaller late-spawned larvae have less opportunity to grow to large adult size. Smaller adults due to reduced food supplies and younger adults due to selection for larvae spawned later in the spring are not mutually exclusive mechanisms and the combination could easily have a nonlinear impact on overall fecundity and population success..

These observations strongly suggest that recent population trends for delta smelt are outside the historical realm of variability and may be associated with a new state of the system (Baxter et al. 2010). This inference is supported by a recent changepoint analysis, which indicated a decline in abundance in the early 2000s independent from environmental variables that previously explained abundance (Thomson et al. 2010). Thus, recovery is likely to require changes in the drivers that have produced the current low levels of abundance and perhaps new drivers or previous drivers that have since become more important.

Given the unprecedented low abundance of delta smelt since 2002 (Figure 2), serious consideration should be given to evaluation of Allee effects. Allee effects occur when reproductive output per fish declines at low population levels (Berec et al. 2006). In other words, below a certain threshold the individuals in a population can no longer reproduce rapidly enough to replace themselves and the population, exhibiting inverse density dependence, spirals to extinction. For delta smelt, possible mechanisms for Allee effects include processes directly related to reproduction and genetic fitness such as difficulty finding mates, genetic drift, and inbreeding (Gascoigne et al. 2009). Other mechanisms related to survival such as increased vulnerability to predation (Gascoigne and Lipcius 2004) are also possible. While theoretical work suggests that Allee effects might be common in nature, empirical evidence for Allee effects in natural populations remains sparse, possibly because they are often masked by measurement errors (Gregory et al. 2010). In addition, the interactive effects of multiple Allee effects may have important implications for species conservation, but have not yet been well explored in ecology (Berec et al. 2006).

Adults

Life History

As already mentioned in Chapter 3, the delta smelt is considered a diadromous seasonal reproductive migrant, and in the winter, many adult delta smelt move upstream into fresh water for spawning (Sommer et al. 2011). These movements may be a specific change in behavior in response to one or more environmental cues, e.g. to the rapid and often dramatic environmental changes during winter-time first flush periods (Sommer et al. 2011; Federal Task Force investigations, unpublished data). It is also possible, however, that the movements do not represent a change in behavior; rather, fish are simply "expanding" their foraging or refuge distribution to habitat upstream when it becomes turbid or otherwise more suitable during and after the first flush period (D. Fullerton, Metropolitan Water District, personal communication). The specific mechanism for the seasonal change in distribution, however, may be more a matter of terminology than of ecological relevance for a fish with as small a home range as delta smelt. Here, we acknowledge the existence of both possibilities, but will use the term "migration" to simply refer to a directed movement upstream occurring prior to and during the spawning season. Using this definition, this seasonal change counts as a migration since it represents a relatively predictable and substantial change in distribution that has adaptive value including potential spawning, foraging and refuge functions (Lucas and Bara 2001). We will refer to it in the remainder of the report as delta smelt "spawning migration."

The delta smelt spawning migration from their low-salinity rearing habitat into freshwater occurs between late December and late February, typically during "first flush" periods when inflow and turbidity increase on the Sacramento and San Joaquin Rivers (Grimaldo et al. 2009, Sommer et al. 2011a). Increased catches of delta smelt in the UFWS Chipps Island Survey and the salvage facilities are unimodal in most years and occur within a couple of weeks of first flush events, suggesting that

adult delta smelt are responding to environmental changes and migrating rapidly upstream once the first flush occurs (Grimaldo et al. 2009 Sommer et al. 2011a). It should be noted that spawning migrations are not always upstream. During occasional periods of very high river flows that spread freshwater habitat throughout much of the estuary, some delta smelt migrate “downstream” from rearing habitats in Suisun Bay and the Delta to freshwater spawning habitats as far west as the Napa River (Hobbs et al. 2007). Also under high flow conditions, it is possible that some delta smelt may not migrate in any direction; if their brackish-water rearing habitat becomes fresh, they can presumably spawn in suitable microhabitats nearby. In addition, there is a small subset of the population that appears to remain in the Cache Slough Complex year around; these fish presumably stay in the region for spawning (Sommer et al. 2011).

Osmerids generally spawn in shallow waters (Moulton 1974, Murawski et al. 1980, Hirose and Kawaguchi 1998, Martin and Swiderski 2001, Bennett 2005). It is believed that delta smelt spawn over sandy substrates in shallow areas based on the observation that first hatch larvae are collected in high concentrations in areas near expansive sandy shoals (Bennett 2005, Grimaldo et al. in review); confirmation of this hypothesis has not been verified through egg collections or observations of spawning adults, except in mesocosm studies (Lindberg et al., in review). Pilot studies to identify egg deposition areas have been conducted by the IEP but these efforts were unsuccessful; it is unknown whether it was due to the method (tiles were used), locations selected, or because of the low probability of detecting eggs from a relatively rare species.

Delta smelt is an opportunistic strategist (Nobriga et al. 2005). Opportunistic strategists are characterized by their short life spans, but high intrinsic rates of population increase driven by rapid maturation and repeat spawns over a protracted spawning season (Winemiller and Rose 1992). In culture, delta smelt can spawn up to four times per year depending on water temperature (Lindberg

personal communication). Recent evidence now indicates that delta smelt can spawn multiple times in the wild if water temperatures stay cool in the later winter and early spring (Wang 2007, L. Damon, CDFW, pers comm 2013). The ability of delta smelt being able to spawn multiple times in the wild could potentially double per capita fecundity over previous estimates for individuals of a specific size. It could also be a contributing factor to the large interannual variability in adult to larvae recruitment (fig. 41).

For adult females, the ability to meet the bioenergetic demands of reproductive development with sufficient food consumption may be important for fish that do produce multiple spawns. Preliminary findings from January through April 2012 indicated that adult smelt are indeed consuming large prey items, such as amphipods, mysids, and larval fish during their spawning period (fig. 38) with feeding incidence near 99% for the period (table. percent age-1 feeding incidence), although feeding rates weren't measured. For this report, we cannot answer if food limitation is a relevant factor during the spring spawning period because this has not been investigated in our comparison years, but we hypothesize that it may be a critical issue for spawners that need energy for multiple spawns.

Table 1. Percent of age-1 delta smelt with food present in the stomach collected January through May 2012.

		Month					Grand Total
Year	Region	Jan	Feb	Mar	Apr	May	
2012	>6	100%	100%				100%
	1-6	100%	100%	100%	100%		100%
	<1	100%	93%	100%	90%		95%
	CS-SRDWSC	100%	100%	100%	96%	100%	99%
Grand Total		100%	99%	100%	95%	100%	99%

Population Trends

Adult delta smelt are monitored by the Spring Kodiak Trawl (SKT) survey which was initiated by CDFW (then CDFG) in 2002 and runs from January to May each year (Honey et al 2008). An

indexing method was recently developed by CDFW for the SKT survey, allowing for year to year comparisons as well as comparisons with the abundance indices for other life stages (Figure 3). The highest SKT index on record was recorded in 2012 (147) and the lowest in 2006 (18). Of the four comparison years, 2005 had the highest SKT index (51), followed by 2010 (27) and 2011 (20) and then 2006 (18). While the SKT index was thus lower in the two wet years than in the two drier years, the SKT index increased substantially in each of the years following the two wet years; however it increased only 2-fold from 2006 to 2007 while it increased 7-fold from 2011 to 2012 (fig. 3).

The annual adult delta smelt abundance indices track the annual abundance indices of sub-adults calculated from the previous years' FMWT survey closely (fig. 44) see also Kimmerer 2008). The relationship is particularly strong at higher fall abundance indices (FMWT index > 50), with more variability at lower abundance indices. Before the POD decline in 2002, all delta smelt FMWT indices were greater than 50 (fig. 3). Thus, the FMWT might provide a useful surrogate for estimating long-term trends in the adult smelt population prior to the initiation of the SKT survey in 2002, but great caution is warranted because this hindcasting would rest on only four data points and assume stable subadult to adult survival relationships and habitat conditions, neither of which is likely true. The Kodiak trawl more efficiently captures delta smelt than the FMWT net. The SKT survey was set up to target delta smelt, while the FMWT survey was designed to monitor young striped bass; however, there is no reason to expect the difference in capture efficiency to affect the relationship, unless such differences were a function of population size (i.e., efficiency was different above and below FMWT=50). While survival from subadults in the fall (FMWT) to adults in the winter and spring (SKT) has been more stable than adult to larvae recruitment and survival between other life stages (fig. 41), it nevertheless shows some variability. Among the four study years, juvenile to adult survival was

greater during the two drier years 2005 and 2010 than during the two wetter years 2006 and 2011 (fig. 41).

Figure 44. Relationship of annual indices of delta smelt abundance from the Spring Kodiak Trawl (SKT) and Fall Widwater Trawl (FMWT) from the previous year. Year labels correspond to the year of the SKT, The R^2 value is for a linear regression.

The number of adult spawners affects population dynamics through production of eggs. Potential reproductive output is proportional to the number of adult female spawners, the size of clutch for females of a specific size, and the number of egg clutches produced by each female. Although egg production in the wild has not yet been documented we can evaluate the relationship of the SKT adult population index to the 20-mm Survey abundance index (fig. 45) and the relationship does not appear to be strong during the POD period (linear regression, $P > 0.05$). This suggests that egg production, assuming that the 20 mm Survey abundance index reflects the number of eggs spawned, is affected by other factors other than adult population size. Clutch sizes were not measured, but annual fork lengths of fish collected in the SKT did not vary greatly (fig. 46). It does not appear that egg batch size should have varied much in the POD years, including the four comparison years 2005-6 and 2010-11, with 2003 as the exception where the median size was greater than 70 mm SL (fig. 46). For delta smelt, which are now considered seasonal indeterminate spawners (i.e., they spawn multiple times), total reproductive output of an individual female should vary with number of eggs per clutch, and the length of the spawning window (the number of days with suitable water temperatures for spawning, see larvae section below), which will influence the number of clutches produced. Obviously, reproductive output will be higher in years when adult females are larger, abundances are higher, and the spawning window is prolonged such that multiple clutches are produced. Note that maximum reproductive output of the adult population at the beginning of spawning is not often realized due to mortality arising from density-

dependent (e.g., food limitation or predation) or density-independent (e.g., entrainment, contaminants) mechanisms. According to Bennett (2011), larvae from bigger, early-spawning females may be disproportionately lost to CVP and SWP entrainment. In any case,, for the purpose of this report, years when there are bigger females and/or a higher spawning stock size will be considered better in terms of reproductive potential than years when adult female size and spawning stock are smaller.

Figure 45. Plot of the Spring Kodiak Trawl adult abundance index against the @0 mm Survey larval abundance index 2003-2012.

Figure 46. Median fork length of delta smelt collected in Spring Kodiak Trawl by year.

Recent investigation of the annual FMWT index values plotted versus the previous years' FMWT index shows that the population has been in a downward trend (Figure 47). The exception was in 2011, when the FMWT index rebounded to pre-POD levels, indicating the population is still able to respond to favorable conditions. The adult smelt population has generally been at such low levels since the POD years that relationships between the FMWT index and the next generation (i.e., 20 mm or TNS) appear to be density independent (Bennett 2005, Maunder and Deriso 2011). This suggests that the delta smelt population does not compensate for reductions in the spawning stock size and that removal of adults from the population effectively reduces reproductive output of the next generation (Kimmerer 2011). However, as noted above, these relationships include stage-to-stage survivals beyond a simple adult to eggs relationship.

Figure 47. Trend in the relationship between Fall Midwater Trawl and Fall Midwater Trawl in the previous year.

Hypotheses.

Hypothesis 1. Hydrology and water exports interact to influence entrainment risk for adult delta smelt

As discussed earlier, we do not currently have a reliable measure of actual entrainment of fishes by the SWP and CVP export pumps. We also do not have actual population abundance estimates for delta smelt. As discussed by Kimmerer (2008, 2011) and Miller (2011), it is thus difficult to estimate proportional population losses due to entrainment. We consider the published proportional loss estimates for adult delta smelt entrainment losses for the two years for which they are available (2005 and 2006; Kimmerer 2008). However, we otherwise restrict our analysis – and this hypothesis – to an assessment of entrainment risk based on salvage and OMR flow data. Note that high entrainment risk does not automatically lead to a high proportion of the population lost to entrainment mortality. For example in wetter years when large numbers of fish are present, but most of the population is distributed farther away from the pumps.

Adult (December-March) delta smelt salvage was highest in 2005 followed by 2006 and 2010 and lowest in 2011 (fig. 48). In 2005, most salvage occurred in January, while in the other three years it occurred in February and March (fig. 49). Overall, adult delta smelt salvage in the four comparison years was on the very low end of the historical time series starting in 1982 (fig. 21). On the other hand, the ratio of adult salvage divided by the previous year's FMWT index was high in 2005 (6th highest on record since 1982), but much lower in 2006 and 2010, and lowest in 2011 (fig. 23).

Figure 48. Annual time series of adult (December-March) delta smelt salvage at the CVP (blue bars) and SWP (green bars) fish protection facilities for 2005-2012.

Figure 49. Annual time series of adult (December-March) delta smelt salvage by month at the CVP (blue bars) and SWP (green bars) fish protection facilities for 2005-2012.

Low salvage levels in these years and especially in 2010 and 2011 were not particularly surprising due to the low FMWT levels of the POD years along with more active management of OMR flows for smelt and salmonid protection after 2008 in accordance with the USFWS (2008) and NMFS (2009) Biological Opinions. For management purposes, the onset of increased adult delta smelt entrainment risk is inferred from distributional patterns of delta smelt found by the SKT survey, delta smelt salvage and, more recently, consideration of Delta conditions, including turbidity patterns. Since 2009, net OMR flows during periods of increased adult delta smelt entrainment risk are now always kept at higher (i.e. flowing more toward the ocean) levels than they were in prior years when net OMR flows were often highly negative (toward the pumps) prior to the April-May export curtailments associated with the Vernalis Adaptive Management Program (VAMP, 2000-2012). This was especially pronounced in the drier first half of the VAMP period (2000-2005, fig. 50). During the four comparison years, winter time (December-March) net OMR flows were least negative in 2006 followed by 2011 and 2010 with the most negative net OMR flows in 2005. Thanks to high inflows, the 2005-6 and 2011 OMR flows were achieved while also maintaining high export pumping. 2010 came at the end of a three year drought and export levels had to be curtailed to achieve the desired OMR flows.

Figure 50. Average flows in cubic feet per second (cfs) in Old and Middle River (OMR) and total exports in millions of acre feet (MAF) for December through March, 1987-2011.

Kimmerer (2008) used salvage, OMR flows, and fish survey data to estimate proportional population losses due to entrainment for the years 1995-2006. The years 2005 and 2006 represent some of the lower loss estimates in the years examined by Kimmerer where mean population losses reached up to 22 % of the adult population in some years when OMR flows were more negative than -5000 cfs (Kimmerer 2008). Even if Kimmerer's estimation method provides a potential overestimate of loss (Miller 2011), proportional losses of the adult population were less than 10% in the two years that

coincide with our comparison years (2005 \approx 3% , 2006 \approx 9%; from fig. 12 in Kimmerer 2008, fig. 12). These types of proportional loss estimates are not available for 2010 and 2011, but would likely be even smaller than for 2005 due to lower salvage, higher OMR flows, and fish distributions away from the CVP and SWP pumps.

In summary, we conclude that hydrology and water exports do interact to influence entrainment risk for adult delta smelt and that adult delta smelt entrainment risk during the four comparison years was perhaps higher in 2005 than in the other years, but was low relative to historical levels in all four years.

Hypothesis 2: Hydrology interacting with turbidity affects predation risk for adult delta smelt.

At present, we do not have information about actual predation mortality varied between the comparison years. As with entrainment, we thus limit our analysis to predation risk. Because delta smelt migrate when the water is generally turbid and during higher flow conditions, it is assumed that losses to visual predators are lower under these conditions. First flush studies underway by the USGS suggest that delta smelt aggregate in the water column during daytime flood tides during upstream migration events, but it is not known if striped bass or Sacramento pikeminnow *Ptychocheilus grandis*, the most likely predators of delta smelt in the water column, can detect and exploit these aggregations.

In the winters of 2005, 2006, 2010, and 2012 the highest Secchi depths (lowest turbidity) were found in the freshwater regions of the estuary (<1 salinity), except for the Cache Slough region in the north Delta which was as turbid as the saltier regions of the estuary (fig. 51). Winter-time Secchi depths in the freshwater region recorded during the SKT surveys were often higher than the average Secchi depths across all IEP EMP monitoring sites during these months since 2003 (about 60 cm) and especially when compared to pre-POD winter Secchi depths (around 50 cm on average) recorded by the

EMP (fig. 20). Winter-time secchi depths in the other regions were generally lower than the EMP Secchi averages for the POD years and more similar to historical averages. In all four comparison years, predation risk associated with turbidity levels was thus likely not different from the historical risk in the more saline regions and the Cache Slough complex, but possibly higher in the freshwater spawning regions of delta smelt except for the Cache Slough region.

Figure 51. Secchi depth data collected during the Spring Kodiak Trawl Survey. Surveys are conducted monthly January-May.

The regional differences were much more pronounced than the interannual differences between the four comparison years. Based on these data, it is not clear that higher flows in 2005 and 2006 contributed to higher turbidity in the winter months. The exception might be toward the end of the delta smelt spawning season in early April when Secchi depths in the freshwater region were often substantially lower in the two wetter years 2006 and 2011 than in the two drier years 2005 and 2010 (fig. 51). This will be discussed further in the report section about larval delta smelt. For adults, we conclude that interannual differences in turbidity between the wetter and drier of the four comparison years did not likely contribute substantially to reduced predation risk and increased survival in the two wetter years.

Hypothesis 3: Predator distribution affects predation risk of adult delta smelt

At present, we do not have information about how predator distribution varied between our comparison years but it is recognized that adult delta smelt could be vulnerable to predation if the distributions of the striped bass and delta smelt populations overlapped. Similarly, if delta smelt utilize littoral habitats to a greater extent than presently assumed, overlap with the distributions of largemouth

bass and other centrarchid populations are possible. As previously mentioned, delta smelt are found in turbid water so this may have reduced their predation risk.

Hypothesis 4: Variability in prey availability affects growth and fecundity (eggs in clutch and multiple clutches) of pre-spawning adult delta smelt.

The conceptual model is that increased food availability leads to not only increased adult survivorship, but also growth, which in turn increases reproductive output (number of eggs per female increases with size; Bennett 2005). In addition, with cooler temperatures and lower metabolic rates, sufficient food resources during winter can contribute to energetically demanding multiple spawning events (three spawns possible in wild fish (L. Damon, CDFW, pers. comm. 2012)).

Examination of growth in response to prey availability is difficult during winter and early spring, due to limited prey data available for current IEP sampling locations. Adult delta smelt diet is varied (fig. 38) and includes pelagic and demersal invertebrates, as well as larval fish. Current mesozooplankton (copepod and cladoceran) and mysid sampling by the EMP Zooplankton Study and invertebrate sampling by the EMP Benthic Monitoring Study does not sample the full geographic range occupied by adult delta smelt, including Cache Slough and the Sacramento River Deep Water Ship Channel. In addition, epibenthic cumaceans and amphipods consumed by delta smelt might not be effectively sampled with current methods via ponar substrate grabs, which is a gear more suited to sampling organisms in or attached to the substrate. Amphipods found in stomachs of adult delta smelt collected December 2011-May 2012 (fig. 38) were 95% *Corophium* spp., and of those, 90% were juveniles ranging 0.8 to 1.3 mm in body length. These amphipods are believed to be mostly juvenile *Americorophium spinicorne* and *A. stimpsoni*, which as adults are tube building amphipods (Hazel and Kelley 1966). Dirt, substrate debris, and tube pieces were not found in delta smelt stomachs with the

amphipods, so it is possible these juveniles amphipods are epibenthic or pelagic prior to settling and building tubes. Size distribution of amphipods collected by the DWR EMP Benthic Monitoring Study is not currently available. The IEP Smelt Larva Survey does collect larval fish data during winter (January-March) over a wide section of the estuary, but comparisons with larval fish consumption by adult delta smelt are limited because the survey was initiated in 2009.

This hypothesis was partially supported by available data on growth of adult female delta smelt, which was highest in 2011 among the four comparison years (fig. 52). Bioenergetics of delta smelt might have been more favorable for growth given generally cooler spring water temperatures (fig. 53).

Figure 52. Individual female lengths by Julian calendar day for mature females collected in the Spring Kodiak Trawl January through May, 2005, 2006, 2010 and 2011. These data include fish captured during both monthly distribution surveys fish and directed surveys. Directed surveys (targeting smelt spawning areas) were discontinued after January 2010.

Figure 53. Water surface temperature data collected during the Spring Kodiak Trawl Survey. Surveys are conducted monthly January-May.

Larvae

Life History

Adult delta smelt, through their selection of spawning sites and spawn timing, largely determine the early rearing habitat and environmental conditions encountered by larvae. Given its annual life cycle, small size at maturity, relatively low fecundity, and small egg size, life history theory suggests that parental care here limited to selection of spawning sites and spawn timing) should be an important factor in reproductive success (Winemiller and Rose 1992). Since eggs have not been detected routinely in the wild, spawning and early rearing habitat locations are inferred from collection of ripe adults and

early stage larvae, which occur from the Delta margins through eastern Suisun Bay (see: <http://www.dfg.ca.gov/delta/projects.asp?ProjectID=SKT>; Wang 1986, 1991, 2007). In culture, delta smelt begin spawning as water temperatures increase to 10-12°C, at which time individual females accompanied by several males select appropriate water velocities and release gametes close to the substrate from dusk to dawn (Baskerville-Bridges et al. 2004, Lindberg et al., In review). In lab experiments, females deposited significantly more eggs on sand and gravel substrates as compared to other substrates offered for egg deposition (Lindberg et al., unpublished data). Based on periodicity in egg deposition in culture, Bennett (2005) proposed that spawning likely coincides with peak tidal currents (i.e. spring tides), which would result in hatching near neap tides. Such a strategy would limit the initial tidal dispersal of larvae.

Larvae hatch after an 11-13 day incubation period at 14.8-16.0°C and begin a short period of buoyancy (or positive phototaxis; Baskerville-Bridges et al. 2004a) prior to slowly settling to the bottom (Mager et al. 2004). In the Delta, tidal and river currents likely act to keep young larvae suspended in the water column. After this buoyant period, Mager et al. (2004) found that larvae were demersal unless actively swimming to feed, which occurred only during daylight hours. Exogenous feeding begins at 5-6 days post-hatch as the last of the yolk sac is resorbed; the lipid globule is resorbed at 10 days (Mager et al. 2004) providing some nutritional reserve if feeding conditions are poor. Larvae probably remain somewhat bottom oriented until swim bladder and fin development are complete at about 65 days of age and about 20 mm TL (Mager et al. 2004, Baskerville-Bridges et al. 2004b), at which time they can fully control their buoyancy and efficiently use tidal and river currents to migrate. The center of distribution for delta smelt larvae and young juveniles is generally downstream of the spawning habitat and associated with X2 during spring (Dege and Brown 2004).

Early larval stages of delta smelt (4-15 mm) tended to be poorly collected by gear previously used in historical SFE egg and larval surveys (Striped Bass Egg and Larva Survey; sled-mounted 500 micron mesh net with 0.38 m² mouth area), but with growth and development greater proportions of the population become vulnerable. This observation led to a sampling gear change in the mid-1990s from the historical egg and larval gear to new gear targeting more vulnerable post-larvae and early juvenile delta smelt (i.e., 20 mm Survey; started in 1995 using a sled-mounted 1600 micron mesh net with 1.5 m² mouth area). The improved catch and distribution information resulting from this change has since proven valuable to the management of delta smelt, and the 20-mm Survey results are now considered essential information (USFSW 2008). In the mid-2000s, an abundance index was developed from 20-mm data (Gleason and Adib-Samii 2007) that has since been used to index abundance trends of larva in spring (e.g., Hieb et al. 2005, Contreras et al. 2011). We use 20-mm Survey abundance indices as one delta smelt end-point to evaluate the support for our hypotheses concerning the environmental drivers and habitat attributes responsible for abundance and survival of larvae.

Population Trends

The highest larval abundance indices on record occurred in the late 1990s, shortly after the initiation of the 20-mm survey in 1995. The lowest larval abundances were observed in 2007-2010 (fig. 3). In 2011, larva abundance improved substantially from the recent minimum in 2007, and achieved levels comparable to those earlier in the 2000s (fig. 3). Although 2011 larval abundance compared favorably to that of 2010, it remained below levels of 2005 and 2006. The modest larva abundance in 2011 was not necessarily indicative of the high stage-to-stage survivals observed later in the year (fig. 41) to produce the highest FMWT index in a decade (fig. 3).

Hypotheses

Hypothesis 1: Delta smelt larvae numbers are affected by adult abundance (and body-condition and size), and the width of the temperature spawning window

To evaluate this hypothesis, we consider adult abundance in the SKT survey, the size (FL) through the spawning season of mature female delta smelt (i.e., maturity stages 4 and 5; Gleason and Adib-Samii 2007; fig. 52), and the number of days in the temperature spawning window as indexed by mean daily water temperatures at Rio Vista between 12 and 20°C. This temperature range was selected as representing a reasonable balance between the various temperature ranges observed in laboratory and field studies (Wang 1986, Baskerville-Bridges et al. 2004b, Bennett 2005) and reviewed in earlier sections of this report. As explained in the previous section on Spawning Adults, adult abundance, based on SKT sampling peaked in 2012 as the 2011 year-class of delta smelt reached maturity (fig. 3). In contrast, the spawning stock (2011 SKT) that produced the 2011 year-class ranked second to 2006 as the lowest adult stock level among those represented in the SKT sampling period (fig. 3). Despite this low level, the 2011 adults produced the highest adult abundance observed to date in 2012. This suggests that within the range of adult abundance variability observed in SKT (fig. 3), adult stock size has not been a limiting factor in subsequent adult recruitment. Even a severely depleted adult stock can still produce a substantial number of larvae and a rebound in the delta smelt population, albeit with lower genetic variability than before (Fisch et al. 2011). It also suggests that factors acting on the survival of larval, juvenile and later stages have a substantial effect on recruitment of adults, because relatively low larval abundance in 2011, was associated with the high 2012 adult abundance (fig. 3). When larval abundance was plotted as a function of adult abundance (fig. 45), adult to larvae recruitment peaked in 2005, was lower in 2006 and 2011 but in the mid-range of 20 mm survey values, and was lowest in 2010. However, in all four years there were more larvae per unit stock than during the

recent years of very low larva abundance 2007-2009 (fig. 3). The adult to larvae recruitment relationship suggests that only 2010 was a relatively poor larva recruitment year based on stock size; or putting it differently, in 2005, 2006 and 2011, environmental factors enhanced survival to the indexed larva stage more so than in 2010.

Mature adult female delta smelt appeared to grow throughout the spawning seasons of the years compared, except 2010 (fig. 52). In 2011, only 13 mature females were collected, so growth estimates are uncertain. In general, the number of mature females collected each year reflected year-class strength as measured by the SKT (fig. 3), except in 2011 when only 13 ripe or ripening females were collected. From these growth trends we infer that environmental conditions were good, supporting both continued growth in length and maturation of eggs.

We used water temperatures at the Rio Vista Bridge as a surrogate for temperatures experienced by spawning delta smelt and calculated the width of the spawning window. We calculated the width of the spawning window as the number of days between the date of first achieving 12°C and the date of first achieving 20°C. The onset of the spawning window occurred earliest in 2010, followed by 2005 and 2011. The spawning window occurred latest in 2006 (fig. 54). The spawning window was broad in both 2005 and 2010 at 129 days, intermediate in 2011 at 113 days (20°C not achieved until July 3, not shown), and was shortest in 2006 at 86 days (fig. 54; Table 2). Assuming that female delta smelt undergo a 35 day refractory period (based on a 4-5 week refractory period reported by Lindberg, U.C. Davis, pers. comm. 2013) between each spawning, even in 2006 three spawnings were possible, assuming fish were mature and ready to spawn at the initiation of the spawning window.

Figure 54. Mean daily temperatures (°C) at Rio Vista from February 1 through June 30, 2005, 2006, 2010, 2011.

Table 2. Delta smelt spawning window for 2005, 2006, 2010 and 2011, defined as number of days of water temperatures 12 to 20°C inclusive, based on mean daily water temperatures measured at Rio Vista. Data are

calendar day when water temperature achieved 12, 17 and 20°C and the duration (days) between those calendar days. The upper limit in 2011 was not reached until July 4, outside the spring season. The temperature range of 14-17°C represents the optimal temperature range for growth.

Year	Day 12°C Achieved	Day 17°C Achieved	Day 20°C surpassed	Duration 12-20	Duration 12-17	Duration 14-17	Duration 17-20
2005	50	118	179	129	68	53	61
2006	84	120	169	85	36	26	49
2010	46	136	174	128	90	57	38
2011	72	163	185	113	91	73	22

Current data provide only partial support for the hypothesis that the numbers (and condition) of adult spawners and length of the spawning window affects larval production. Good recruitment to the larval stage in 2005 was consistent with relatively higher adult abundance and size (fig. 3 and 52), and by a long spawning window (129 days; table 2). In contrast, 2006 with low adult abundance (fig. 3), low adult female size (fig. 52) and the shortest spawning window (85 days) among years compared also resulted in relatively good larva abundance (fig. 3). Among the factors investigated here, there was only a possible indication of what led to poor larvae numbers in 2010: adult abundance was moderate, the spawning window long, but ripening and ripe females were not detected after early April and female growth through the winter was poor (fig. 52). Finally, the spawning window was fairly long in 2011 as compared to 2006, so higher larval production in 2011 is consistent with the hypothesis. As noted above, the 2011 larval production was surprisingly high despite low adult abundance, which contrasts somewhat with expectations in the hypothesis..

Hypothesis 2: Food availability affects larva abundance and survival.

This hypothesis focuses on the transition of the zooplankton community and changes in abundances of food items most often consumed by delta smelt larvae; some of these zooplankton are

also believed to be affected by temperature. Consumption of juvenile and adult calanoid copepods, particularly *E. affinis* and *P. forbesi*, comprised most of the larval diet through June (Nobriga 2002, Slater and Baxter submitted). *E. affinis* is moderately abundant only during winter and spring and rare in summer and fall, whereas *P. forbesi* is abundant only in summer and fall (Durand 2010, Hennessy 2010, 2011, Winder and Jassby 2011). It's not clear whether the seasonal decline in abundance of *E. affinis* is related to temperature, potential competitive interactions with *P. forbesi* or to a seasonal change in filtration by *P. amurensis* (Miller and Stillman 2013). The transition between high abundances of the two species, may create a seasonal 'food gap' during late spring or early summer and has been hypothesized as an important period for delta smelt larval survival (Bennett 2005, Miller et al. 2012).

To assess whether a gap in availability existed between *E. affinis* and *P. forbesi* abundance periods we looked at abundance patterns in 20 mm Survey copepod data for stations with and without delta smelt. The food gap hypothesis was only weakly supported by data. The density of *E. affinis* (in the presence of delta smelt larvae) typically reached 100 m⁻³ by week 16 (fig. 55 and 56). Assuming 100 m⁻³ as a baseline density for *E. affinis*, this baseline was generally maintained until about week 22, when they declined at about the same time that *P. forbesi* densities increased to 100 m⁻³ (fig. 55 and 56). If the densities of both *E. affinis* and *P. forbesi* are combined and tracked through time, there was a gap in food during week 22 (late May – early June) of 2005 (fig. 28). Such density gaps were not observed in other comparison years (fig. 28 and 29).

Figure 55. Densities by calendar week of *Eurytemora affinis* and *Pseudodiaptomus forbesi* from mesozooplankton sampling by the CDFW 20mm and Summer Townet surveys, 2005 and 2006.

Figure 56. Densities by calendar week of *Eurytemora affinis* and *Pseudodiaptomus forbesi* from mesozooplankton sampling by the CDFW 20mm and Summer Townet surveys, 2010 and 2011.

Hypothesis 3: Distribution and abundance of Mississippi silverside, temperature, turbidity, and food availability interact to influence predation risk/rate on larval delta smelt.

Mississippi silversides are ubiquitous within the Delta (Brown and May 2006) and have long been proposed (Bennett 1995) and more recently confirmed as a predator of delta smelt larvae (Baerwald et al. 2012). We do not have estimates of proportional predation losses to silversides during the four study years and thus focus on assessing predation risk by evaluating fish distributions, size, and growth.

Relatively large silversides are present in the Delta during spring and are likely to prey upon delta smelt larvae. Silverside habitat has been characterized as open water shoals and shoreline (Brown and May 2006, Grimaldo et al. 2012); however, the species also occurs in low density in deep open water primarily in summer (Grimaldo et al. 2012). Catches in Spring Kodiak Trawl confirm silverside presence in open water in spring as well, though catches tend to be low. Compared to the open embayments, catches are higher in channels such as Montezuma Slough, Cache Slough, the Sacramento Deepwater Ship Channel, and especially the most upstream sampling station in the Stockton Deepwater Ship Channel (table 3). In contrast, delta smelt larvae were found in significantly higher densities in offshore-open water habitats (Grimaldo et al. 2004), which corresponds to the habitat where silversides consuming delta smelt larvae were captured (Baerwald et al. 2012). As discussed above, the relatively large-sized silversides present in the Spring Kodiak Trawl indicates some offshore overlap of foraging silversides with delta smelt larval habitat.

Table 3. Mississippi silverside catch by region (monthly sample number in parentheses) and year by the Spring Kodiak Trawl Survey sampling monthly March through May (months when delta smelt larvae are present), 2005, 2006, 2010 and 2011; distribution survey data only. Annual sampling effort summarized consisted of 3 surveys and 37 stations. Tow volume varied substantially, but averaged 6,300 m³ per tow for the 4 years.

Region	2005	2006	2010	2011	Total Catch	Total Catch per Trawl
Suisun Bay (n=10)	1	1	2	1	5	0.04
Montezuma Sl (n=3)	51	4	17	22	94	2.61
Lower Sacramento R (n=4)	10	1	1	3	15	0.31
Cache Sl (n=3)	9	2	4	2	17	0.47
Sac DeepWater Ship Channel (n=1)	14	20	45	22	101	8.42
San Joaquin R (n=8)	39	9	11	14	73	0.76
Moklemne R. (n=5)	1	1	1	8	11	0.18
South Delta (n=3)	1	0	1	1	3	0.08
Annual Total for regions	126	38	82	73	319	

The frequency and magnitude of silverside catches by the Spring Kodiak Trawl increased as Secchi depths approached and dropped below 50 cm (fig. 57), suggesting that silversides may venture offshore more frequently and in higher numbers in turbid water. This might also represent a displacement effect resulting from high flows, but high catches were most common in Montezuma Slough and the Sacramento Deepwater Ship Channel (table 3) where flow should not have been a factor.

Figure 57. Scatter plot of Mississippi silverside catch plotted on Secchi depth (cm) at location of capture from the Spring Kodiak Trawl Survey, 2005, 2006, 2010 and 2011.

The hypothesis is somewhat supported in that: 1) silversides are captured in Spring Kodiak Trawl in March and April (fig. 58), when early stage delta smelt larvae are abundant; 2) silverside catches offshore increase with increased turbidity (i.e., declining Secchi depth; fig. 57), and 3) there is regional overlap in Cache Slough and the Sacramento Deepwater Ship Channel, and some in Montezuma Slough (cf. table 3 and http://www.dfg.ca.gov/delta/data/20mm/CPUE_map.asp), known larval rearing regions. However the catch per trawl (table 3) indicates low densities and the same turbidity that facilitates offshore movement may also inhibit predation effectiveness. Overall, this

predation effect is deemed weak and not likely to affect delta smelt larval survival except in rare regional and temporal circumstances when a larvae and silversides are present in high numbers.

Figure 58. Monthly length frequency of Mississippi silversides captured by the Spring Kodiak Trawl during distribution sampling March – May in the Sacramento River and Cache Slough sampling stations only, 2002-2012. The months and geographic range were selected to overlap with that of delta smelt larvae as they hatch and begin to grow.

In general, mortality rate of prey fish declines as their body size increases. This observation has been reported by many researchers (see Bertram 1996). has been reported by many researchers (see Bertram 1996). Paradis et al. (1996) found that predation is maximal when larvae lengths were 10% of the length of the predator and dropped rapidly thereafter. Silversides collected in the Kodiak Trawl in spring ranged in size mostly between 50 and 90 mm FL (fig. 58). Assuming maximal predation at 10% of predator length (Paradis et al. 1996), silverside predation would be maximal on delta smelt larvae from 5 to 9 mm FL and then decline. Based on size at age data from fish in laboratory culture, larvae would be vulnerable to high rates of silverside predation for approximately 20 days post-hatch (Mager et al. 2004).

We currently do not have larval growth data in terms of fish length. Instead, we used otolith data (e.g., otolith increments and days post-hatch; fig. 59) to determine relative growth rates and estimate predation windows, given certain assumptions. (fig. 59).. Assuming the median distance in microns from the otolith core at day 20 represents larva size at day 20, we then projected when that size was achieved on average in all years (i.e., where growth curves cross horizontal blue line projected on ‘days from core’, (fig. 59a). We also assume that larvae reach approximately 10 mm in length on day 20 (see Mager et al. 2004), at which point they would experience much lower risk of predation by silversides.

2214 **Figure 59.** a) Otolith growth (microns from core) in relation to days post-hatch for years 2005, 2006, 2010 and
2215 2012 (Cook et al. 2012, unpublished data). Assume that growth to 10 mm occurs in about 20 days on average,
2216 then identify approximate median in microns from otolith (horizontal line), then project vertical lines from where
2217 median crosses growth curves to determine variation in days to achieve 10 mm (vertical blue lines); b) results
2218 from a) plotted on the annual duration of optimal growth temperatures, which depicts the mean number of days
2219 susceptible to predation goes down for the population as the days of optimal temperature increases.

2220 This hypothesis that faster growing, larger delta smelt larvae and juveniles are less susceptible to
2221 silverside predation was generally supported by early larval growth results, but not by food density
2222 results. The slowest growth, and thus the longest period of vulnerability to silverside predation,
2223 occurred in 2006, coincident with the shortest period with temperatures in the optimal range (i.e., 14-
2224 17°C; fig. 59b); however, *E. affinis* density at 20 mm Survey stations was distinctly higher in early to
2225 mid-spring 2006 in the LSZ (salinity 1-6) in relation to the other comparison years (fig. 60). The
2226 highest growth rate was achieved in 2011 (fig. 59a), a wet year with a prolonged duration within
2227 optimal growth range (Table 2) and perhaps the second highest mid- to late-spring *E. affinis* density at
2228 stations with delta smelt larvae among comparison years (fig. 60).

2229 **Figure 60.** Adult *E. affinis* densities (number m⁻³) collected per salinity group (>6, 1-6, and <1 ppt) and in the
2230 Cache Slough-Sacramento River Deep Water Ship Channel by the 20 mm Survey during surveys conducted
2231 biweekly from mid-March to mid-June in 2005-2006 and 2010-2011.

2232

2233 *Hypothesis 4: Hydrology and exports interact to influence direction of transport and risk of entrainment*
2234 *for larval delta smelt.*

As for adults, we do not have proportional entrainment estimate for all four study years, so the entrainment portion of this hypothesis cannot be directly evaluated for the study years. Instead, we use information on the density of larvae in the central and south Delta and estimates of channel currents to infer risk of entrainment. Among the study years only 2005 larva entrainment was estimated by Kimmerer (2008), and loss to the population was relatively low. Based only on densities of larvae in the central and south Delta (table 4), risk of entrainment was also highest among comparison years in 2005. Larvae (<20 mm) entrained in the state and federal water export systems are generally not quantified, though presence-absence records have been kept since water year 2010 (ftp://ftp.delta.dfg.ca.gov/salvage/Daily_Smelt_Summary/).

Using net daily averaged OMR flows for March through May as a surrogate for larva entrainment (fig. 24), we find that in general, the adult to larvae recruitment index varies positively with March – May OMR flows in the 4 study years, although recruitment in 2005 was higher than in 2010 even though OMR was more negative in the 2005 than in the 2010. The year 2005 was somewhat wetter than 2010, and it is interesting to note that the summed Sacramento and San Joaquin Valley water year indices almost perfectly predicted adult to larval recruitment in these four years as well as in the other years, except for 2008 (fig. 43). This relationship suggests that overall hydrology (and perhaps overall climate) and its interactions with other environmental drivers has a very strong effect on the habitat available for delta smelt spawning and larval rearing. This includes the effect of hydrology on OMR flows and entrainment, but likely also on many of the other habitat attributes shown in the conceptual models presented here (figs. 9-12).

Looking more closely at net daily OMR flows from March to June, we find that these such flows were moderately negative (i.e., toward the export pumps) only in March 2005, and were zero to weakly positive in April and May; also, Qwest was strongly positive from late March through early June

and exports were low from late April through late May (fig. 24). The other dry year, 2010 exhibited a similar pattern, but lower inflows resulted in the magnitude of exports more directly influencing OMR flows (fig. 24), and leading to moderately negative OMR flows in March and again in June, but only weakly negative flows in April and most of May coincident with positive Qwest. In the high outflow years 2006 and 2011, few larvae were detected in the central or south Delta (table 4) and Qwest flows were strongly positive from March through at least early June, while OMR flows were near zero or weakly negative in March and positive to strongly positive by April and continuing to early June of both years (fig. 44). Thus, entrainment was unlikely to be a factor during either wet year and was probably not a substantial factor in either dry year.

Table 4. Mean monthly catch of delta smelt per 10,000 m3 by station for stations in the south and central Delta for the 20mm Survey, 2005, 2006, 2010, 2011. Non-zero values are bolded.

Year = 2005		Months				
Station	March	April	May	June	July	
809	0.00	0.00	6.27	10.34	0.00	
812	0.00	0.00	6.27	13.32	0.00	
815	0.00	6.12	6.78	0.00	0.00	
901	0.00	0.00	6.41	0.00	7.21	
902	0.00	0.00	0.00	0.00	0.00	
906	3.30	5.86	6.44	0.00	0.00	
910	0.00	0.00	0.00	0.00	0.00	
912	0.00	0.00	0.00	0.00	0.00	
914	6.37	2.97	3.12	0.00	0.00	
915	0.00	0.00	0.00	0.00	0.00	
918	3.03	2.83	0.00	0.00	0.00	
919	0.00	0.00	0.00	0.00	0.00	
Year = 2006		Months				
Station	March	April	May	June	July	
809	0.00	0.00	0.00	0.00	0.00	
812	0.00	0.00	0.00	0.00	0.00	
815	0.00	0.00	2.48	0.00	0.00	
901	0.00	0.00	0.00	0.00	0.00	
902	0.00	0.00	0.00	0.00	0.00	
906	0.00	0.00	0.00	0.00	0.00	

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910	0.00	0.00	0.00	0.00	0.00
912	0.00	0.00	0.00	0.00	0.00
914	0.00	0.00	0.00	0.00	0.00
915	0.00	0.00	0.00	0.00	0.00
918	0.00	0.00	0.00	0.00	0.00
919		0.00	0.00	0.00	0.00

Year = 2010		Months				
Station	March	April	May	June	July	
809	0.00	0.00	3.24	0.00	0.00	
812	0.00	0.00	0.00	0.00	0.00	
815	0.00	3.53	3.44	0.00	0.00	
901	0.00	0.00	0.00	0.00	0.00	
902	0.00	0.00	0.00	0.00	0.00	
906	0.00	6.73	0.00	3.29	0.00	
910	0.00	10.48	0.00	0.00	0.00	
912	0.00	0.00	0.00	0.00	0.00	
914	0.00	0.00	0.00	0.00	0.00	
915	0.00	0.00	0.00	0.00	0.00	
918	0.00	0.00	0.00	0.00	0.00	
919	0.00	0.00	0.00	0.00	0.00	

Year = 2011		Months				
Row Labels	March	April	May	June	July	
809	0.00	0.00	0.00	3.46	0.00	
812	0.00	0.00	0.00	0.00	0.00	
815	0.00	0.00	0.00	0.00	0.00	
901	0.00	0.00	7.38	0.00	0.00	
902	0.00	0.00	0.00	0.00	0.00	
906	0.00	0.00	0.00	0.00	0.00	
910	0.00	0.00	0.00	0.00	0.00	
912	0.00	0.00	0.00	0.00	0.00	
914	0.00	0.00	0.00	0.00	0.00	
915	0.00	0.00	0.00	0.00	0.00	
918	0.00	0.00	0.00	0.00	0.00	
919	0.00	0.00	0.00	0.00	0.00	

Juveniles

Life History

During summer juvenile delta smelt primarily rear in west Delta, Suisun Bay, and Cache Slough Complex (Moyle 2002, Bennett 2005, Merz et al. 2011, Sommer and Mejia 2013). As in late spring and fall, the center of distribution of the fish occurs in the low salinity zone. The degree to which the fish use particular geographic areas depends on salinity, temperature, and turbidity (Nobriga et al. 2008); other factors that may affect their summer distribution include *Microcystis* distribution, and possibly prey density, bathymetric features, or other water quality constituents.

Population Trends

Relative abundance of juvenile delta smelt is presently indexed by the Summer Townet Survey (TNS). The survey was not designed specifically to measure delta smelt abundance and catches are low (Honey et al. 2004). Nonetheless, patterns in the annual abundance index provide a useful basic measure of population trends.

The TNS index rebounded substantially in 2011, but declined to a value consistent with low recent year indices in 2012 (fig. 3). This pattern of persistently low abundance is consistent with the POD, which began over a decade ago (Sommer et al. 2007; Thomson et al 2010). During the last decade, TNS abundance indices were especially low from 2005-2009 (fig. 3). The index rebounded somewhat in 2010 and then strongly rebounded in 2011, but in 2012 went back to a lower level similar to 2010. The onset of the 2005-2009 period of low juvenile abundance was characterized by extremely low larvae to juvenile survival in 2005 and 2006 (fig. 41). Larval survival to juveniles recovered somewhat in the following years, but TNS indices stayed low (fig. 3). Historically high levels of delta smelt abundance during summer apparently allowed density dependent effects to occur between summer

and fall in some years; this conclusion was still supported after the species declined in the early 1980s, but the apparent carrying capacity was lower (Bennett 2005). The available trawl data suggest that this trend of declining carrying capacity has continued as suggested by the very low Fall Midwater Trawl indices produced by a range of juvenile TNS abundance levels (fig. 61).

Figure 61. Relationships between TNS and resulting FMWT indices for several different time periods. Multiple time periods are included to illustrate that there is evidence of declining carrying capacity and density dependent effects in the delta smelt population during both the pre- and post-POD eras.

Hypotheses

Hypothesis 1: At very low population levels, delta smelt population dynamics are driven by density-independent relationships.

The TNS results were consistent with expectations based on the population trends described above. In other words, juvenile delta smelt abundance in 2005, 2006, 2010, and to a lesser degree in 2011 was relatively low (fig. 3). This was expected based on the very low abundance of maturing adults in the preceding year as indexed by the FMWT as well as the low abundance of adults indexed by the SKT which closely tracked the FMWT indices (fig. 3). This assumes that sufficient resources were available to support more delta smelt

Hypothesis 2: High water temperatures reduce delta smelt growth and survival through lethal and sublethal (bioenergetic stress; reduced distribution) effects.

High water temperatures have a strong effect on juvenile delta smelt survival (Swanson et al. 2000). In addition to the obvious potential for lethal effects, temperature can have sub-lethal effects such as reduced habitat area, higher prey requirements, and increased predation. The potential for increased prey requirements and increased predation is described below for other hypotheses.

The general pattern observed in the TNS temperature data during the target years was that summer 2005 and 2006 temperatures were relatively higher than 2010 and 2011 during July and August (e.g. TNS surveys 3-5; fig. 13). Temperatures during survey 4 and 5 may have been particularly important as they exceeded lethal levels in freshwater at some sites, suggesting the potential for mortality. Note that this does not mean that temperatures were universally cooler in 2010 and 2011 than in 2005 and 2006; for example the region around Cache Slough had relatively high temperatures in August 2010. Based on these observations we expected that conditions would have been more favorable in 2010 and 2011; however, juvenile to subadult survival (as measured by the ratio of FMWT to the TNS) was highest in 2011 and lowest in 2010 (fig. 41). The temperature and survival data therefore were not entirely consistent with our hypothesis.

At this point, our data and analyses are inadequate to address temperature effects on delta smelt growth. Although there are some data for delta smelt growth during several of the target years, it is difficult to separate the relative effects of improved bioenergetics (see below) versus simple ontogenetic changes in fish size. Juvenile fish growth rates are typically not constant and change with size (“allometric effects”; Fuiman 1983). Specifically, daily growth rates (e.g mm/day) are often faster for smaller fish and slower for older fish. Hence, cooler years may delay delta smelt transitions from faster to slower growth phases, yielding a relatively fast measured growth rate at a specific point in time (e.g., September) because at that specific time the fish are still relatively young and still on the “steepest” part of an idealized growth curve. For example, it is unclear whether relatively fast juvenile growth rates in July 2011 (J. Hobbs, UC Davis, unpublished data) were a result of better food availability or cool temperatures that delayed development.

Hypothesis 3. Distribution and abundance of striped bass, temperature, and turbidity influence predation risk/rate on juvenile delta smelt

Characterizing predation risk is exceptionally complicated, making it difficult to generate simple hypotheses that describe associated losses of delta smelt. We hypothesize that subadult (age 1-3) striped bass are the major predator on juvenile delta smelt and that losses are likely affected by temperature and turbidity patterns. However, other factors likely affect predation risk and several factors may interact. As noted above for temperature and below for food, high temperatures and low prey density likely lead to bioenergetics problems and increased foraging activity, which might reduce predator avoidance behavior (e.g., Marine and Cech 2004) in delta smelt. These effects may be compounded by low turbidity, which makes delta smelt more visible to predators in their habitat. Although higher striped bass abundance could theoretically result in greater consumption of prey including delta smelt (Loboschefskey et al. 2012), changes in habitat variables for both species such as food, temperature, and turbidity mean that predation rates on delta smelt periodically may be independent of predator abundance. Although there has been substantial progress in modeling (Loboschefskey et al. 2012, Nobriga et al. 2013) and genetic methods (Baerwald et al. 2012), there is not yet a standardized way to assess the effects of predation on delta smelt. Moreover, there are no effective surveys to assess age 1-3 striped bass abundance or distribution. Therefore, we are unable to directly evaluate this hypothesis. Lacking this information, we can at least examine turbidity and temperature patterns for the four years. Temperature responses were described for Hypothesis 2. In general, summer 2005 and 2006 temperatures were relatively higher than 2010 and 2011 during key summer months (e.g. TNS surveys 3-5; fig. 13). We expect that cooler temperatures in 2010 and 2011 may have contributed to reduced predation on delta smelt. Turbidity data are limited to 2010 and 2011 (fig. 62). There were no

consistent differences between the two years. Secchi depth data did not suggest major differences among the 4 years except at salinities >6 when 2005-2006 had higher values in some months (fig. 63).

Figure 62. Turbidity data collected during the Summer Townet Survey. Surveys are conducted biweekly June-August. Note different scales among salinity regions.

Figure 63. Secchi depth data collected during the Summer Townet Survey. Surveys are conducted biweekly June-August.

Hypothesis 4. Juvenile delta smelt growth and survival is affected by food availability.

As for Hypothesis 2, we are currently unable to evaluate the growth data because water temperature affects development time, and because growth curves are complicated by allometric effects. The general conceptual model is that higher food abundance results in faster growth rates and larger, healthier fish. In addition, larger, healthier delta smelt are presumably less vulnerable to predators because of increased size making them difficult for smaller predators to capture and consume. Both benthic grazing and hydrologic effects are known to adversely affect phytoplankton biomass (Cloern and Jassby 2012), which in turn is thought to depress abundance of zooplankton food supplies for delta smelt. In general, the median abundance of some of the key prey such as calanoid copepods is highest in summer months (fig. 64) when juvenile delta smelt are present; however, the range of observed densities is broad in all months. As noted previously, Kimmerer (2008) found that delta smelt survival from summer to fall was positively associated with calanoid copepod biomass in the low salinity zone.

Figure 64. Trends in calanoid copepods (number/m³ for all taxa combined) collected by the IEP Environmental Monitoring Program (EMP) during each the four study years (2005, 2006, 2010, and 2011).

Interpretation of the field data is complicated because there are no long-term IEP EMP study stations located in some of the core habitats for delta smelt, for example, Cache Slough and the Sacramento River Deep Water Ship Channel. Moreover, densities of calanoid copepods vary among regions based on differing habitat (temperature and salinity) requirements of each species (fig. 65).

Figure 65. Trends in calanoid copepods (number/m³ for all types combined) collected by the IEP Environmental Monitoring Program (EMP) in three salinity ranges (>6 ppt; 1-6 ppt; <1 ppt) during each the four study years (2005, 2006, 2010, and 2011)..

Phytoplankton data (chlorophyll-*a*) suggest that the base of the food web was most enhanced in July and August 2011 and relatively depleted in 2005 (fig. 66). There is some evidence that these changes may have affected zooplankton abundance. For example, summer densities of calanoid copepods in the LSZ and <1 ppt regions also tended to be highest in 2011 as compared to the other years (fig. 65). This pattern generally held when individual taxa are considered including two of the most important food sources for delta smelt, *Eurytemora affinis* (fig. 27) and *Pseudodiaptomus forbesi* (fig. 28).

Figure 66. Trends in chlorophyll-*a* concentrations (µg/L) collected by the IEP Environmental Monitoring Program during each the four study years (2005, 2006, 2010, and 2011).

Of the selected recent years, juvenile to subadult survival (as measured by the ratio of FMWT to the TNS) was highest in 2011 and lowest in 2010 (fig. 41). If food availability was the primary habitat attribute, our expectation was that summer prey abundance would have been higher in 2011 than 2010. Figure 64 suggests that prey levels were higher in July and August of 2011 than 2010. Calanoid copepod levels varied across the different salinity ranges, but generally followed the same pattern (fig. 65). In addition, calanoid copepod densities (fig. 64), along with juvenile survival (fig. 41), were

higher in 2006 than 2005. Hence, the prey data only partially support this hypothesis. Since fish bioenergetics includes the interaction of both food availability and water temperature, this does not mean that food availability was unimportant. To the contrary, both summer 2010 and 2011 had relatively cool temperatures as compared to 2005 and 2006, so there may still have been complicated bioenergetic effects. In addition, recent studies (Slater, DFW, unpublished data) indicate that delta smelt consumption was not just limited to calanoid copepods, so our assessment does not reflect the full dietary range.

Hypothesis 5. Juvenile delta smelt survival and growth is reduced by harmful algal blooms (HAB) because of direct (habitat quality and toxic effects) and indirect (food quality and quantity) effects.

The appearance of late-summer HAB, especially *Microcystis*, is thought to be another component of the decline in habitat quality for delta smelt (Baxter et al. 2010; Lehman et al. 2010). Direct effects may include toxicity on delta smelt and a reduced area of suitable habitat. There also may be indirect effects on food quantity and quality, particularly with respect to their zooplankton prey (Ger et al. 2009; 2010a,b; Lehman et al. 2010).

The growth responses of delta smelt during the four target years are still unclear (see below), but there is evidence that delta smelt juvenile to subadult survival (as measured by the ratio of FMWT to the TNS) was highest 2011 and lowest in 2010 (fig. 41). If HAB were the dominant habitat feature, we would expect that *Microcystis* blooms would follow the same pattern. This seems to have been the case as *Microcystis* levels were low during the TNS in 2011 as compared to 2010 across a range of salinities (fig. 67). Unfortunately, similar data are not available for 2005 and 2006. In general, our expectation is that 2006 *Microcystis* levels would have been relatively low as a result of higher flow levels that discourage blooms (Lehman et al. 2005).

2424 **Figure 67.** Summer Townet Survey mean visual rank of *Microcystis* spp. (ranks 1-5 possible; 1 = absent) observed
2425 at all stations during biweekly surveys (1-6) in various salinity regions (>6, 1-6, and <1 ppt) and in the CS-
2426 SRDWSC during June through August 2010 and 2011. Observations were not made in Cache Slough-
2427 Sacramento River Deepwater Ship Channel (CS-SRDWSC) during 2010.

2428 **Subadults**

2429 **Life History**

2430 During fall subadult delta smelt primarily rear in west Delta, Suisun Bay, and Cache Slough
2431 Complex (Moyle 2002, Bennett 2005, Sommer and Mejia 2013); the center of distribution is in the low-
2432 salinity zone (Sommer et al. 2011). The degree to which the fish use particular geographic areas
2433 depends on salinity and turbidity (Feyrer et al. 2007). Other factors that may affect their fall distribution
2434 include *Microcystis* distribution and water temperature in the early fall (September-October), and
2435 possibly prey density, bathymetric features, or other water quality constituents.

2436 **Population Trends**

2437 Population trends for subadult delta smelt are presently indexed by the FMWT. Although like
2438 the TNS, the survey was not designed specifically to measure delta smelt relative abundance and catches
2439 are low (Honey et al. 2004, Newman 2008), the data are nonetheless a useful basic measure of
2440 population trends, except perhaps at very low abundance (i.e., FMWT index values less than about 50;
2441 fig. 3). However, the general agreement between the FMWT and subsequent Spring Kodiak Trawl
2442 (SKT) sampling suggests that FMWT results (fig. 44) are a reasonable indicator of general trends in
2443 abundance.

2444 The FMWT index rebounded substantially in 2011, but declined to a value consistent with low
2445 recent year indices in 2012 (fig. 4). This pattern of low abundance is consistent with the POD, which

began over a decade ago (Sommer et al. 2007, Thomson et al 2010). During the last decade, FMWT indices were especially low from 2005-2010 (fig. 42). After the rebound in 2011, the index went back to a lower level similar to the 2005-2010 period. Since 2003, the juvenile to subadult survival index was lowest in 2004. During the four study years, the juvenile to subadult survival index was lowest in 2010, but relatively high in the other three years and highest in 2011 (fig. 41).

Historically, high levels of delta smelt abundance during summer apparently resulted in density-dependent mortality between summer and fall in some years (Bennett 2005); this conclusion was still supported after the species declined in the early 1980s, but the apparent carrying capacity, meaning the magnitude of the FMWT index relative to the TNS index, was lower (fig. 61). The available FMWT data suggest that these trends of density-dependent mortality during the summer-fall and declining carrying capacity have continued (fig. 61). The close correlation of the FMWT and SKT (fig. 44) indicates that the factors likely affecting survival of delta smelt to the adult spawning population operate earlier in the life cycle. Additional mortality certainly occurs between the FMWT and SKT but the lack of variability around the regression line suggests there is not a lot of variability in the rate of that mortality. Thus, the relative annual spawning stock appears to be largely determined by fall of the birth year.

Hypotheses

Hypothesis 1: At very low population levels, delta smelt population dynamics are driven by density-independent relationships.

Compensatory density dependence predicts that a fish's population growth or survival rates can increase when abundance is low and decrease if abundance increases beyond a carrying capacity (Rose et al. 2001). Delta smelt abundance was very low at the beginning of 2011 (see the 2010 FMWT index or 2011 SKTS index; fig. 3). The expectation of density dependent theory is that survival should (if

conditions allow) increase because abundance was low relative to carrying capacity. Therefore, the sudden increase in subadult abundance in 2011 is consistent with the higher survival predicted by compensatory density dependence at low population abundance coupled with widespread availability of good habitat conditions throughout the year. However, given the fact that years classes 2005-06 and 2010, or any POD year other than 2011, did not suggest a compensatory response prevents concluding that a compensatory relations was the primary reason for the comparatively stronger 2011 year-class revealed by the FMWT index. This would suggest density independent factors operating at population levels below carrying capacity. Thus the hypothesis is generally supported but caution is warranted given the small data set.

Hypothesis 2. Subadult delta smelt growth and survival is affected by food availability.

Similar to juveniles, the general conceptual model is that higher food abundance results in faster growth rates and subsequently, lower predation loss (e.g., Houde 1987; Sogard 1997; Takasuka et al. 2003); however the opposite situation in which the fastest growing fishes are most vulnerable to predators has also been observed in at least one east coast estuary (Gleason and Bengtson 1996). In general, fall calanoid copepod abundance and cladocera abundance were higher in 2011 in freshwater and the low-salinity zone compared to the other years, particularly 2005 and 2006 (figs. 65 and 31). However, these data are highly variable, so this conclusion does not apply to each region in every month. With that caveat, the data generally support the hypothesis that on average, prey density was higher for subadult delta smelt in 2011, when populations were larger, which is presumably related to higher survival. As noted above, we are currently unable to evaluate whether delta smelt grew faster in 2011 because water temperature affects spawning and hatch dates, which complicates the interpretation of growth rates.

Hypothesis 3. Distribution and abundance of striped bass, temperature, and turbidity influence predation risk/rate on subadult delta smelt

As already described for juvenile delta smelt, predation risk is exceptionally complicated, making it difficult to generate simple hypotheses that describe associated losses of delta smelt. The data are not currently available to test this hypothesis (e.g., juvenile striped bass abundance estimates for 2005-2011 have only been developed for 1981-2004 (Loboschewsky et al. 2012), and there are no description of the juvenile striped bass functional response to variation in delta smelt density or its interaction with environmental conditions like temperature and turbidity). Thus, beyond its potential consistency with the turbidity results presented below, no firm conclusion can be made.

Hypothesis 4. Subadult delta smelt survival and growth is reduced by harmful algal blooms (HAB) because of direct (habitat quality and toxic effects) and indirect (food quality and quantity) effects.

The appearance of late-summer harmful algal blooms (HAB), especially *Microcystis*, is thought to be another detriment to habitat quality for delta smelt (Baxter et al. 2010; Lehman et al. 2010). Direct effects may include toxicity to delta smelt and a reduced distribution if the fish try to limit their overlap with the bloom. There also may be indirect effects on food quantity and quality, particularly with respect to their zooplankton prey (Ger et al. 2009; 2010a,b; Lehman et al. 2010).

The growth responses of delta smelt during the four target years are still unclear (see above), but there is evidence that summer juvenile to subadult survival was highest in 2011, and subadult to adult survival was moderate (fig. 41). Our expectation is therefore that HAB were less prevalent in 2011 than 2005, 2006 or 2010. As already described for juveniles, the hypothesis that the *Microcystis* bloom would be less intense in 2011 than in 2010 was supported for freshwater habitats, but not completely for the LSZ (fig. 67). These results were similar for subadults, with the highest occurrence of HAB in

September in the low salinity zone (fig. 68). This may be an indication that the higher outflow in September-October 2011 displaced the bloom seaward. The comparatively high delta smelt FMWT index that coincided with this shift in *Microcystis* distribution is not consistent with the hypothesis; however, the visual survey results presented here are only semiquantitative and do not necessarily reflect the potential for differences in actual toxicity among years. Therefore, no conclusion is possible at this time.

Figure 68. Fall Midwater Trawl mean visual rank of *Microcystis* spp. (ranks 1-5 possible; 1 = absent) observed at all stations during monthly surveys in various salinity regions (>6, 1-6, and <1 ppt) and in the CS-SRDWSC during September through December 2010 and 2011.

Hypothesis 5. Subadult delta smelt survival and growth are affected by the size and position of the low salinity zone during fall.

We do not address this hypothesis in detail because it is the subject of an adaptive management experiment (FLaSH) described earlier (Reclamation 2011, 2012; see also <http://deltacouncil.ca.gov/science-program/fall-low-salinity-habitat-flash-studies-and-adaptive-management-plan-review-0>). According to the FLASH conceptual model, conditions are supposed to be favorable for delta smelt when X2 is approximately 74 km or less, unfavorable when X2 is approximately 85 km or greater, and intermediate in between (Reclamation 2011, 2012). Surface area for the LSZ at X2s of 74 km and 85 km were predicted to be 4000 and 9000 hectares, respectively (Reclamation 2011, 2012). The data generally supported the idea that lower X2 and greater area of the LSZ would support more subadult delta smelt (table 5). The greatest LSZ area and lowest X2 occurred in 2011 and were associated with a high FMWT index. There was little separation between the other years on the basis of X2, LSZ area, or FMWT index (Table 5). The position and area of the LSZ is a

key factor determining the quantity and quality of low salinity rearing habitat available to delta smelt and other estuarine species (see Chapter 4 for more detail..

Table 5. Mean and standard deviation (SD) for X2, surface area of low salinity zone (M. McWilliams, Delta Modeling Associates, unpublished data), and values of the Fall Midwater Trawl index (FMWT) for abundance of subadult delta smelt.

	X2 (km)		Surface area LSZ (hectares)		FMWT index
Year	Mean	SD	Mean	SD	
2005	83	2	4889	252	26
2006	82	3	4978	320	41
2010	85	2	4635	226	29
2011	75	1	8366	133	343

Chapter 6: Synthesis, 2012 Update, and Next Steps

NOTE TO REVIEWERS OF THE JULY 2013 DRAFT MAST REPORT:

Chapter 6 remains under development. At this time, only an outline is available for review.

Final text will be developed after revisions to the conceptual framework and evaluation of hypotheses in response to review comments.

Caveats:

-Report is intended as a working document, not as the final word on delta smelt.

Key Points:

1. Multiple factors are important to delta smelt.
2. Many factors interact in complex ways (e.g. flow and geographic effects on turbidity; temperature effects on survival, growth and predation)

3. All seasons help to determine year class strength.

4. Success of delta smelt in 2011 was related to moderate to high stage-to-stage survivals over the entire year.

5. Low survival between any two life stages may result in low production of mature adults

Overall next steps:

1. Consider approaches to continually organizing, analyzing, synthesizing, and communicating results about delta smelt responses to changing habitat conditions;

2. Evaluate approaches to facilitating quantitative modeling of delta smelt;

3. Evaluate additional data and information needs concerning delta smelt;

4. Consider approaches to understand the effects of the wide variety of management actions targeting delta smelt, including adaptive management of fall outflow, entrainment, habitat restoration, etc.;

5. Develop key “indicator” variables that can be used to track and predict the status of delta smelt and its habitat and serve as “performance metrics” to evaluate the success of management actions.

References Cited

- Aasen, G.A. In press. Predation on salvaged fish during the collection, handling, transport, and release phase of the State Water Project's John E. Skinner Delta Fish Protective Facility. Technical Report. Interagency Ecological Program of the Sacramento-San Joaquin Estuary. Sacramento, California.
- Acuña S, Deng D-F, Lehman P, and Teh S. 2012a. Sublethal dietary effects of *Microcystis* on Sacramento splittail, *Pogonichthys macrolepidotus*. *Aquatic Toxicology* 110–111:1– 8.
- Acuña S, Baxa D, Teh S. 2012b. Sublethal dietary effects of microcystin producing *Microcystis* on threadfin shad, *Dorosoma petenense*. *Toxicon* 60:1191-1202.
- Afentoulis V., J. Dubois, and R. Fujimura. In press. Stress response of delta smelt, *Hypomesus transpacificus*, in the collection, handling, transport and release phase of fish salvage at the John E. Skinner Delta Fish Protective Facility. California Department of Fish and Wildlife. Technical Report. Interagency Ecological Program of the Sacramento-San Joaquin Estuary. Sacramento, California.
- Aksnes, D. L., and J. Giske. 1993. A theoretical model of aquatic visual feeding. *Ecological modeling* 67:233-250.
- Alpine, A.E., and Cloern, J.E., 1992, Trophic interactions and direct physical effects control phytoplankton biomass and production in an estuary: *Limnology and Oceanography* v. 37, p. 946-955.
- Anderson, J. T. 1988. A review of size dependent survival during pre-recruit stages of fishes in relation to recruitment. *Journal of Northwest Atlantic Fish Society* 8:55-66.
- Arthur, J.F., Ball, M.D., and Baughman, S.Y., 1996, Summary of federal and state water project environmental impacts in the San Francisco Bay-Delta estuary, California, *in* Hollibaugh, J.T., ed., *San Francisco Bay: the ecosystem*: Pacific Division American Association for the Advancement of Science, San Francisco, California. p. 445-495.

- 2594 Baerwald, M.R., Schreier, B.M., Schumer, G., and May, B., 2012, Detection of threatened delta smelt
2595 in the gut contents of the invasive Mississippi silverside in the San Francisco Estuary using TaqMan
2596 Assays: Transactions of the American Fisheries Society, v. 141, p.1600–1607.
- 2597 Baskerville-Bridges, B, Lindberg, JC, Doroshov, SI. 2004a. The effect of light intensity, alga
2598 concentration, and prey density on the feeding behavior of delta smelt larvae. American Fisheries
2599 Society Symposium 39:219-228.
- 2600 Baskerville-Bridges, B., J. C. Lindberg, J. V. Eenennaam, and S. I. Doroshov. 2004b. Delta smelt
2601 research and culture program 5-year summary, 1998-2003. University of California Davis, Davis,
2602 California.
- 2603 Baskerville-Bridges, B., J. C. Lindberg, and S. I. Doroshov. 2005. Manual for the intensive culture of
2604 delta smelt (*Hypomesus transpacificus*). University of California Davis, Department of Animal
2605 Science, Davis, CA.
- 2606 Baxter, R., Breuer, R., Brown, L., Chotkowski, M., Feyrer, F., Gingras, M., Herbold, B., Mueller-
2607 Solger, A., Nobriga, M., Sommer, T., and Souza, K. 2008. Pelagic organism decline progress report.
2608 2007 synthesis of results: Interagency Ecological Program for the San Francisco Estuary, Technical
2609 Report 227, 86 p.
- 2610 Baxter, R., Breuer, R., Brown, L., Conrad, L., Feyrer, F., Fong, S., Gehrts, K., Grimaldo, L., Herbold,
2611 B., Hrodey, P., Mueller- Solger, A., Sommer, T., and Souza. K., Interagency Ecological Program
2612 2010 Pelagic Organism Decline work plan and synthesis of results: Interagency Ecological Program
2613 for the San Francisco Estuary, Stockton, CA, 259 p. Available at:
2614 <http://www.water.ca.gov/iep/docs/FinalPOD2010Workplan12610.pdf>
- 2615 Bennett, W. A. 1995. Potential effects of exotic inland silversides on delta smelt. Interagency Ecological
2616 Program for the Sacramento-San Joaquin Estuary Newsletter 8(1):4-6.

- 2617 Bennett, W.A. 2005. Critical assessment of the delta smelt population in the San Francisco Estuary,
2618 California: San Francisco Estuary and Watershed Science 3(2). Available at:
2619 <http://escholarship.org/uc/item/0725n5vk>
- 2620 Bennett, W. A. 2011. The "big-mama" hypothesis: evaluating a subtle link between water export
2621 operations and the decline of delta smelt. Final Report submitted to: Mark Gowdy, State Water
2622 Resources Control Board, Sacramento, California. 11 pages.
- 2623 Bennett, W.A., and Moyle, P.B., 1996, Where have all the fishes gone? Interactive factors producing
2624 fish declines in the Sacramento San Joaquin Estuary, in Hollibaugh, J.T., ed., San Francisco Bay: the
2625 ecosystem: Pacific Division American Association for the Advancement of Science, San Francisco,
2626 California, p. 519–542.
- 2627 Bennett, W.A., J.A. Hobbs, and S.J. Teh. 2008. Interplay of environmental forcing and growth-selective
2628 mortality in the poor year-class success of delta smelt in 2005. Final report: “fish otolith and condition
2629 study 2005”. Prepared for the POD Management Team of the Interagency Ecological Program for the
2630 San Francisco Estuary.
- 2631 Bennett, W. A., W. J. Kimmerer, and J. R. Burau. 2002. Plasticity in vertical migration by native and
2632 exotic estuarine fishes in a dynamic low-salinity zone. *Limnology and Oceanography* 47(5):1496-
2633 1507.
- 2634 Berec, L., E. Angulo, and F. Courchamp. 2006. Multiple Allee effects and population management.
2635 *Trends in Ecology and Evolution* 22:185–191.
- 2636 Bertram, D. F. 1996. Size-dependent predation risk in larval fishes: mechanistic inferences and levels of
2637 analysis. *Fishery Bulletin* 94:371-373.

- Blumberg, A., P. Goodwin, E. Houde, S. Monismith, T. M. Powell, C. Simenstad. 2010. Review of IEP and other Bay-Delta modeling focused on hydrodynamics and fish. Report by the IEP Science Advisory Group, available at <http://www.water.ca.gov/iep/docs/IEPModelWorkshopReview.pdf>.
- Bouley, P. and W.J. Kimmerer. 2006. Ecology of a highly abundant, introduced cyclopoid copepod in a temperate estuary. *Marine Ecology Progress Series* 324:219–228.
- Brander, S.M., I. Werner, J.W. White, and L.A. Deanovic. 2009. Toxicity of a dissolved pyrethroid mixture to *Hyaella azteca* at environmentally relevant concentrations. *Environmental Toxicology and Chemistry* 28:1493–1499.
- Brooks, M.L., Fleishman, E., Brown, L.R., Lehman, P.W., Werner, I., Scholz, N., Mitchelmore, C., Lovvorn, J.R., Johnson, M.L., Schlenk, D., van Drunick, S., Drever, J.I., Stoms, D. M., Parker, A. E., and Dugdale, R., 2012, Life histories, salinity zones, and sublethal contributions of contaminants to pelagic fish declines illustrated with a case study of San Francisco Estuary, California, USA: *Estuaries and Coasts*, v. 35, p. 603-621.
- Brown, L.R., and Michniuk D., 2007, Littoral fish assemblages of the alien-dominated Sacramento–San Joaquin Delta, California, 1980–1983 and 2001–2003: *Estuaries and Coasts*, v. 30, p. 186–200.
- Brown, L., and J. May. 2006. Variation in spring nearshore resident fish species composition and life histories in the lower Sacramento-San Joaquin watershed and delta. *San Francisco Estuary and Watershed Science* 4(1):1-15.
- Brown, L.R., and Moyle, P.B., 2005, Native fish communities of the Sacramento-San Joaquin watershed, California: a history of decline: *American Fisheries Society Symposium*, v. 45, p. 75–98.
- Brown, L.R., W.A. Bennett, R.W. Wagner, T. Morgan-King, N. Knowles, F. Feyrer, D.H. Schoellhamer, M.T. Stacey, M. Dettinger. 2013. Implications for future survival of delta smelt from

- 2660 four climate change scenarios for the Sacramento-San Joaquin Delta, California. *Estuaries and Coasts*
2661 36:754-774.
- 2662 Brown, R., S. Greene, P. Coulston and S. Barrow. 1996. An evaluation of the effectiveness of fish
2663 salvage operations at the intake to the California aqueduct, 1979–1993. Pages 497–518 in J. T.
2664 Hollibaugh, editor. *San Francisco Bay: the ecosystem*. Pacific Division of the American Association
2665 for the Advancement of Science, San Francisco, CA.
- 2666 Brown, T. 2009. Phytoplankton community composition: the rise of the flagellates. *IEP Newsletter*
2667 22(3):20–28.
- 2668 Bryant, M.E. and J.D. Arnold. 2007. Diets of age-0 striped bass in the San Francisco Estuary, 1973–
2669 2002. *California Fish and Game* 93(1):1–22.
- 2670 Carlton, J.T., J.K. Thompson, L.E. Schemel, and F.H. Nichols. 1990. Remarkable invasion of San
2671 Francisco Bay (California, USA) by the Asian clam *Potamocorbula amurensis* I. Introduction and
2672 dispersal. *Marine Ecology Progress Series* 66:81–94.
- 2673 Castillo, G., Morinaka, J., Lindberg, J., Fujimura, R., Baskerville-Bridges, B., Hobbs, J., Tigan, G., and
2674 Ellison, L., 2012, Pre-screen loss and fish facility efficiency for delta smelt at the south Delta's State
2675 Water Project, California: *San Francisco Estuary and Watershed Science*, v. 10, no. 4, p. 1-23.
- 2676 Clark, K.W., M.D. Bowen, R.B. Mayfield, K.P. Zehfuss, J.D. Taplin, and C.H. Hanson. 2009.
2677 Quantification of pre-screen loss of juvenile steelhead in Clifton Court Forebay. State of California.
2678 The California Natural Resources Agency. Department of Water Resources. Fishery Improvements
2679 Section Bay-Delta Office. 119 pp.
- 2680 Cloern, J.E., 1987, Turbidity as a control on phytoplankton biomass and productivity in estuaries:
2681 *Continental Shelf Research*, v. 7, p. 1367-1381.

- 2682 Cloern, J. E., and A. D. Jassby. 2012. Drivers of change in estuarine-coastal ecosystems: Discoveries
2683 from four decades of study in San Francisco Bay, *Rev. Geophys.*, 50, RG4001,
2684 doi:10.1029/2012RG000397.
- 2685 Cloern, J.E., N. Knowles, L.R. Brown, D. Cayan, M.D. Dettinger, T.L. Morgan, D.H. Schoellhamer,
2686 M.T. Stacey, M. van der Wegen, R.W. Wagner, A.D. Jassby. 2011. Projected Evolution of
2687 California's San Francisco Bay-Delta-River System in a Century of Climate Change. *PlosONE*
2688 6(9):e24465.
- 2689 Cohen, A.N. and J.T. Carlton. 1998. Accelerating invasion rate in a highly invaded estuary. *Science*,
2690 279: 555-558.
- 2691 Conomos, T.J. (ed.). 1979. San Francisco Bay: the urbanized estuary. Investigation into the natural
2692 history of San Francisco Bay and Delta with reference to the influence of man: Pacific Division
2693 American Association for the Advancement of Science, San Francisco, California.
- 2694 Contreras, D., V. Afentoulis, K. Hieb, R. Baxter, and S. Slater. 2011. 2010 Status and Trends Report for
2695 pelagic fishes of the upper San Francisco Estuary. *IEP Newsletter* 24(2):27-38.
- 2696 Cummins, K. W., and J. C. Wuycheck. 1971. Caloric equivalents for investigations in ecological
2697 energetics. *Mitteilungen-Internationale Vereinigung für Theoretische und Angewandte Limnologie*
2698 18:1-158.
- 2699 Davis, N. D. 1993. Caloric content of oceanic zooplankton and fishes for studies of salmonid food
2700 habits and their ecologically related species. (NPAFC Doc.) FRI-UW-9312. Fisheries Research
2701 Institute, University of Washington, Seattle. 10 pp.
- 2702 Dege, M., and Brown, L.R., 2004, Effect of outflow on spring and summertime distribution and
2703 abundance of larval and juvenile fishes in the upper San Francisco Estuary: American Fisheries
2704 Society Symposium, v. 39, p. 49–65.

- 2705 Dettinger, M.D., 2011, Climate change, atmospheric rivers and floods in California—A multimodel
2706 analysis of storm frequency and magnitude changes: *Journal of American Water Resources*
2707 Association, v. 47, p. 514–523.
- 2708 DiGennaro, B.; Reed, D.; Swanson, C.; Hastings, L.; Hymanson, Z.; Healey, M.; et al., 2012, Using
2709 Conceptual Models in Ecosystem Restoration Decision Making: An Example from the Sacramento-
2710 San Joaquin River Delta, California. *San Francisco Estuary and Watershed Science*, 10(3).
2711 [jmie_sfews_11181](http://www.escholarship.org/uc/item/3j95x7vt). Retrieved from: <http://www.escholarship.org/uc/item/3j95x7vt>
- 2712 Dugdale, R.C., F.P. Wilkerson, and A.E. Parker. 2013. A biogeochemical model of phytoplankton
2713 productivity in an urbanestuary: The importance of ammonium and freshwater flow. *Ecological*
2714 *Modelling* 263:291–307.
- 2715 Dugdale, R.C., Wilkerson, F.P., Hogue, V.E., and Marchi, A., 2007, The role of ammonium and nitrate
2716 in spring bloom development in San Francisco Bay: *Estuarine, Coastal, and Shelf Science*, v. 73, p.
2717 17–29.
- 2718 Durand, J. R. 2010. Determinants of seasonal abundance of key zooplankton of the San Francisco
2719 Estuary. M.S. Ecology and Systematics, San Francisco State University, San Francisco. 55 pages.
- 2720 Essington, TE, Hansson, S. 2004. Predator-dependent functional responses and interaction strengths in a
2721 natural food web. *Canadian Journal of Fisheries and Aquatic Sciences* 61:2215-2226.
- 2722 Feyrer, F., B. Herbold, S.A. Matern, and P.B. Moyle. 2003. Dietary shifts in a stressed fish assemblage:
2723 Consequences of a bivalve invasion in the San Francisco Estuary. *Environmental Biology of Fishes*
2724 67:277–288.
- 2725 Feyrer, F., Brown, L.R., Brown, R.L., and Orsi, J.J., eds., 2004 Early life history of fishes in the San
2726 Francisco Estuary and Watershed: American Fisheries Society Symposium 39, American Fisheries
2727 Society, Bethesda, Maryland.

- 2728 Feyrer, F., Nobriga, M.L., and Sommer, T.R., 2007, Multi-decadal trends for three declining fish
2729 species: habitat patterns and mechanisms in the San Francisco Estuary, California, USA: Canadian
2730 Journal of Fisheries and Aquatic Sciences, v. 64, p. 723–734.
- 2731 Feyrer, F., Newman, K., Nobriga, M., and Sommer, T., 2010, Modeling the effects of future freshwater
2732 flow on the abiotic habitat of an imperiled estuarine fish: Estuaries and Coasts, v. 34, p. 120–128.
- 2733 Fish, M., D. Contreras, V. Afentoulis, J. Messineo, and K. Hieb. 2009. 2008 Fishes annual status and
2734 trends report for the San Francisco Estuary. IEP Newsletter 22(2):17–36.
- 2735 Fisch, K.M., Henderson, J.M., Burton, R.S., and May B., 2011, Population genetics and conservation
2736 implications for the endangered delta smelt in the San Francisco Bay-Delta: Conservation Genetics, v.
2737 12, p. 1421–1434.
- 2738 FLASH Panel (Fall Low Salinity Habitat (FLASH) Study Review Panel). 2012. Fall Low Salinity Habitat
2739 (FLASH) Study Synthesis – Year One of the Delta Fall Outflow Adaptive Management Plan, Review
2740 Panel Summary Report. Delta Science Program, Sacramento, CA. available at:
2741 [http://deltacouncil.ca.gov/sites/default/files/documents/files/FallOutflowReviewPanelSummaryReport](http://deltacouncil.ca.gov/sites/default/files/documents/files/FallOutflowReviewPanelSummaryReport_Final_9_11.pdf)
2742 [_Final_9_11.pdf](http://deltacouncil.ca.gov/sites/default/files/documents/files/FallOutflowReviewPanelSummaryReport_Final_9_11.pdf)
- 2743 Fuiman, L. A. 1983. Growth gradients in fish larvae. Journal of Fish Biology 23:117–123.
- 2744 Ganju, N.K., Schoellhamer, D.H., Murrell, M.C., Gartner, J.W., and Wright, S.A., 2007, Constancy of
2745 the relation between flock size and density in San Francisco Bay, in Maa, J.P.-Y., Sanford, L.P., and
2746 Schoellhamer, D.H., ed., Estuarine and Coastal Fine Sediments Dynamics: Elsevier Science B.V., p.
2747 75-91.
- 2748 Gascoigne, J., L. Berec, S. Gregory, and F. Courchamp. 2009. Dangerously few liaisons: a review of
2749 mate-finding Allee effects. Population Ecology 51:355–372.

- Ger, K.A., Arneson, P., Goldman, C.R., and Teh, S.J., 2010b, Species specific differences in the ingestion of *Microcystis* cells by the calanoid copepods *Eurytemora affinis* and *Pseudodiaptomus forbesi*: Journal of Plankton Research, v. 32, p. 1479–1484.
- Ger, K.A., Teh, S.J., Baxa, D.V., Lesmeister, S. and Goldman, C.R., 2010a, The effects of dietary *Microcystis aeruginosa* and microcystin on the copepods of the upper San Francisco Estuary: Freshwater Biology, v. 55, p. 1548–1559.
- Ger, K.A., Teh, S.J., and Goldman, C.R., 2009, Microcystin-LR toxicity on dominant copepods *Eurytemora affinis* and *Pseudodiaptomus forbesi* of the upper San Francisco Estuary: Science of the Total Environment, v. 407, p. 4852–4857.
- Gifford, S.M., G. Rollwagen-Bollens, S.M. Bollens. 2007. Mesozooplankton omnivory in the upper San Francisco Estuary. Marine Ecological Progress Series 348:33–46.
- Gingras, M. 1997. Mark/recapture experiments at Clifton Court Forebay to estimate pre-screening loss to juvenile fishes: 1976–1993. Interagency Ecological Program. Technical Report 55.
- Gleason, E.C. and J. Adib-Samii. 2007. 20mm Metadata. Available at: <ftp://ftp.dfg.ca.gov/>
- Gleason, T.R., and D.A. Bengtson. 1996. Growth, survival and size-selective predation mortality of larval and juvenile inland silversides, *Menidia beryllina*. Journal of Experimental Marine Biology and Ecology 199:165-177.
- Glibert, P.M., 2012, Ecological stoichiometry and its implications for aquatic ecosystem sustainability: Current Opinion in Environmental Sustainability: v.4, p. 272–277.
- Glibert, P.M., Fullerton, D., Burkholder, J.M., Cornwell, J.C., and Kana, T.M., 2011, Ecological stoichiometry, biogeochemical cycling, invasive species, and aquatic food webs: San Francisco Estuary and comparative systems: Reviews in Fisheries Science, v. 19, p. 358–417.

- 2772 Gould, A.L. and W.J. Kimmerer. 2010. Development, growth, and reproduction of the cyclopoid
2773 copepod *Limnoithona tetraspina* in the upper San Francisco Estuary. Marine Ecology Progress Series
2774 412:163–177.
- 2775 Gregory, R.S., Levings, C.D. 1998. Turbidity reduces predation on migrating juvenile Pacific salmon.
2776 Transactions of the American Fisheries Society 127:275-285.
- 2777 Gregory, S.D., C.J.A. Bradshaw, B.W. Brook, and F. Courchamp. 2010. Limited evidence for the
2778 demographic Allee effect from numerous species across taxa. Ecology 91:2151–2161.
- 2779 Grimaldo, L.F., R.E. Miller, C.M. Peregrin, and Z.P. Hymanson. 2004. Spatial and temporal distribution
2780 of native and alien ichthyoplankton in three habitat types of the Sacramento-San Joaquin Delta, p. 81–
2781 96. In: F. Feyrer, L. R. Brown, R. L. Brown, and J. J. Orsi (eds.), Early life history of fishes in the San
2782 Francisco Estuary and watershed. American Fisheries Society Symposium 39, Bethesda, Maryland.
- 2783 Grimaldo, L.F., Sommer, T., Van Ark, N., Jones, G., Holland, E., Moyle, P., Herbold, B., and Smith, P.,
2784 2009, Factors affecting fish entrainment into massive water diversions in a tidal freshwater estuary:
2785 Can fish losses be managed?: North American Journal of Fisheries Management, v. 29, p. 1253–1270.
- 2786 Grimaldo, L., R.E. Miller, C.M. Peregrin, and Z. Hymanson. 2012. Fish assemblages in reference and
2787 restored tidal freshwater marshes of the San Francisco Estuary. San Francisco Estuary and Watershed
2788 Science, 10(1). Retrieved from: <http://escholarship.org/uc/item/52t3x0hq>
- 2789 Hallfredsson, E., and T. Pedersen. 2009. Effects of predation from juvenile herring (*Clupea harengus*)
2790 on mortality rates of capelin (*Mallotus villosus*) larvae. Canadian Journal of Fisheries and Aquatic
2791 Sciences 66: 1693-1706.
- 2792 Hall, L.S., P.R. Krausman, and M.L. Morrison, 1997, The habitat concept and a plea for standard
2793 terminology. Wildl. Soc. Bull. 25:173-182.

- 2794 Hartman, K. J. and S. B. Brandt. 1995. Comparative energetics and the development of bioenergetics
2795 models for sympatric estuarine piscivores. Canadian Journal of Fisheries and Aquatic Science. 52:
2796 1647-1666.
- 2797 Hirose, T, Kawaguchi, K. 1998. Spawning ecology of Japanese surf smelt, *Hypomesus pretiosus*
2798 japonicus (Osmeridae), in Otsuchi Bay, northeastern Japan. Environmental Biology of Fishes 52:213-
2799 223.
- 2800 Houde, E. D. 1989. Comparative growth, mortality, and energetics of marine fish larvae: temperature
2801 and implied latitudinal effects. Fishery Bulletin 87:471-495.
- 2802 Hennessy, A. 2010. Zooplankton monitoring 2009. IEP Newsletter 23(2):15-22.
- 2803 Hennessy, A. 2011. Zooplankton monitoring 2010. Interagency Ecological Program for the Sacramento-
2804 San Joaquin Estuary Newsletter 24(2):20-27.
- 2805 Hennessy, A., and T. Enderlein. 2013. Zooplankton monitoring 2011. Interagency Ecological Program
2806 for the San Francisco Estuary Newsletter 26(1):23-30.
- 2807 Hestir, E.L.. 2010. Trends in estuarine water quality and submerged aquatic vegetation invasion. PhD
2808 Dissertation. Davis: University of California.
- 2809 Hieb, K., M. Bryant, M. Dege, T. Greiner, K. Souza and S. Slater. 2005. Fishes in the San Francisco
2810 Estuary, 2004 Status and Trends. Interagency Ecological Program Newsletter 18(2):19-36.
- 2811 Hjort, J. 1914. Fluctuations in the great fisheries of northern Europe viewed in light of biological
2812 research. Rapports et Procès-verbaux des Réunions Conseil international pour l'Exploration de la Mer
2813 19:1-228
- 2814 Hobbs, J. A., W. A. Bennett, and J. E. Burton. 2006. Assessing nursery habitat quality for native smelts
2815 (*Osmeridae*) in the low-salinity zone of the San Francisco estuary. Journal of Fish Biology 69:907-
2816 922.

- 2817 Hobbs, J.A., W.A. Bennett, J. Burton, and M. Gras. 2007. Classification of larval and adult delta smelt
2818 to nursery areas by use of trace elemental fingerprinting. *Transactions of the American Fisheries*
2819 *Society* 136:518–527.
- 2820 Hollibaugh, J.T., ed., 1996, *San Francisco Bay: the ecosystem*: Pacific Division American Association
2821 for the Advancement of Science, San Francisco, California.
- 2822 Hunter, J. R. 1980. The feeding behavior and ecology of marine fish larvae. Pages 287-330 in J. E.
2823 Bardach, J. J. Magnuson, R. C. May, and J. M. Reinhart, editors. *Fish behavior and its use in the*
2824 *capture and culture of fishes*, volume ICLARM Conference Proceedings 5. International Center for
2825 *Living Aquatic Resources Management*, Manila, Philippines. 512 pages
- 2826 IEP (Interagency Ecological Program for the San Francisco Estuary). 2005. Interagency Ecological
2827 Program 2005 Work plan to evaluate the decline of pelagic species in the upper San Francisco
2828 Estuary. Available at: [http://www.science.calwater.ca.gov/pdf/workshops/POD/2005_IEP-](http://www.science.calwater.ca.gov/pdf/workshops/POD/2005_IEP-POD_Workplan_070105.pdf)
2829 [POD_Workplan_070105.pdf](http://www.science.calwater.ca.gov/pdf/workshops/POD/2005_IEP-POD_Workplan_070105.pdf).
- 2830 Jassby, A.D., 2008, *Phytoplankton in the upper San Francisco Estuary: recent biomass trends, their*
2831 *causes and their trophic significance*: *San Francisco Estuary and Watershed Science*, v. 6, no. 1,
2832 available at <http://www.escholarship.org/uc/item/71h077r1>.
- 2833 Jassby, A.D., Cloern, J.E., and Cole, B.E., 2002, Annual primary production: patterns and mechanisms
2834 of change in a nutrient-rich tidal ecosystem: *Limnology and Oceanography*, v. 47, p. 698–712.
- 2835 Jassby, A.D., Kimmerer, W.J., Monismith, S.G., Armor, C., Cloern, J.E., Powell, T.M., Schubel, J.R.,
2836 and Vendlinski, T.J., 1995, Isohaline position as a habitat indicator for estuarine populations:
2837 *Ecological Applications*, v. 5, p. 272–289.
- 2838 Johnson, M.L., Werner, I., Teh, S., and Loge, F., 2010, Evaluation of chemical, toxicological, and
2839 histopathological data to determine their role in the pelagic organism decline: University of

- 2840 California, Davis, Final report to the California State Water Resources Control Board and Central
2841 Valley Regional Water Quality Control Board.
- 2842 Jung, S. and E. D. Houde. 2004. Recruitment and spawning-stock biomass distribution of bay anchovy
2843 (*Anchoa mitchilli*) in Chesapeake Bay. Fishery Bulletin, U.S. 102:63-77.
- 2844 Honey, K., R. Baxter, Z. Hymanson, T. Sommer, M. Gingras, and P. Cadrett,. 2004. IEP long-term fish
2845 monitoring program element review. Interagency Ecological Program for the San Francisco Bay/Delta
2846 Estuary, Technical Report 78. 67 pages plus appendices
- 2847 Kimmerer, W. J., 2002a, Physical, biological, and management responses to variable freshwater flow
2848 into the San Francisco Estuary: Estuaries, v. 25, p. 1275–1290.
- 2849 Kimmerer, W.J., 2002b, Effects of freshwater flow on abundance of estuarine organisms: physical
2850 effects or trophic linkages: Marine Ecology Progress Series, v. 243, p. 39–55.
- 2851 Kimmerer, W.J., 2004, Open-water processes of the San Francisco Estuary: from physical forcing to
2852 biological responses: San Francisco Estuary and Watershed Science, v. 2, available at
2853 <http://escholarship.org/uc/item/9bp499mv>
- 2854 Kimmerer, W.J. 2006. Response of anchovies dampens effects of the invasive bivalve *Corbula*
2855 *amurensis* on the San Francisco Estuary foodweb. Marine Ecology Progress Series 324:207–218.
- 2856 Kimmerer, W.J. 2008. Losses of Sacramento River Chinook salmon and delta smelt to entrainment in
2857 water diversions in the Sacramento-San Joaquin Delta. San Francisco Estuary and Watershed Science.
2858 Vol. 6, Issue 2, Article 2.
- 2859 Kimmerer, W.J. 2011. Modeling delta smelt losses at the South Delta Export Facilities. San Francisco
2860 Estuary and Watershed Science, 9(1). Available at: <http://www.escholarship.org/uc/item/0rd2n5vb>

- 2861 Kimmerer, W. J., and M. L. Nobriga. 2008. Investigating particle transport and fate in the Sacramento-
2862 San Joaquin Delta using particle tracking model. *San Francisco Estuary and Watershed Science* 6(1,
2863 Article 4):26 pp.
- 2864 Kimmerer, W.J., and Orsi, J.J., 1996, Changes in the zooplankton of the San Francisco Bay estuary
2865 since the introduction of the clam *Potamocorbula amurensis*, in Hollibaugh, J.T., ed., *San Francisco*
2866 *Bay: the ecosystem*: Pacific Division American Association for the Advancement of Science, San
2867 Francisco, California, p. 403-423
- 2868 Kimmerer, K.J., N. Ferm, M.H. Nicolini, and C. Penalva. 2005. Chronic food limitation of egg
2869 production in populations of copepods of the genus *Acartia* in the San Francisco Estuary. *Estuaries*
2870 28:541–550.
- 2871 Kimmerer, W.J., Gartside, E., and Orsi, J.J., 1994, Predation by an introduced clam as the likely cause
2872 of substantial declines in zooplankton of San Francisco Bay: *Marine Ecology Progress Series*, v. 113,
2873 p. 81–93.
- 2874 Kimmerer, W.J., Gross, E.S., and MacWilliams, M.L., 2009, Is the response of estuarine nekton to
2875 freshwater flow in the San Francisco Estuary explained by variation in habitat volume?: *Estuaries and*
2876 *Coasts*, v. 32, p. 375–389.
- 2877 Kimmerer, W., J. Stillman, and L. Sullivan. 2011. Zooplankton and clam analyses in support of the
2878 Interagency Ecological Program's Work Plan on Pelagic Organism Declines (POD). Final report to
2879 the POD management team. Romberg Tiburon Center for Environmental Studies, San Francisco State
2880 University.
- 2881 Kimmerer, W.J., J.H. Cowan, Jr., L.W. Miller, and K.A. Rose. 2000. Analysis of an estuarine striped
2882 bass (*Morone saxatilis*) population: influence of density-dependent mortality between metamorphosis
2883 and recruitment. *Canadian Journal of Fisheries and Aquatic Sciences* 57: 478–486.

- 2884 Kitchell, J.F., L.A. Eby, X. He, D.E. Schindler, and R. A. Wright. 1994. Predator-prey dynamics in an
2885 ecosystem context. *Journal of Fish Biology* 45, Issue Supplement sA:209–226.
- 2886 Kuivila, K. M., and C.G. Foe. 1995. Concentrations, transport and biological effects of dormant spray
2887 pesticides in the San Francisco Estuary, California. *Environmental Toxicology and Chemistry*
2888 14:1141–1150.
- 2889 Kuivila, K. and G.E. Moon. 2004. Potential exposure of larval and juvenile delta smelt to dissolved
2890 pesticides in the Sacramento–San Joaquin Delta, California. Pages 229–241 in F. Feyrer, L. R. Brown,
2891 R. L. Brown, and J. J. Orsi, editors. *Early life history of fishes in the San Francisco Estuary and*
2892 *watershed*. American Fisheries Society, Symposium 39, Bethesda, Maryland.
- 2893 Laprise, R., and J. J. Dodson. 1989. Ontogeny and importance of tidal vertical migrations in the
2894 retention of larval smelt *Osmerus mordax* in a well-mixed estuary. *Marine Ecology Progress Series*
2895 55:101-111.
- 2896 Leggett, W. C., and E. Deblois. 1994. Recruitment in marine fishes: is it regulated by starvation and
2897 predation in the egg and larval stages? *Netherland Journal of Sea Research* 32(2):119-134.
- 2898 Lehman, P.W., Boyer, G., Hall, C., Waller, S., and Gehrts, K., 2005, Distribution and toxicity of a new
2899 colonial *Microcystis aeruginosa* bloom in the San Francisco Bay Estuary, California: *Hydrobiologia*,
2900 v. 541, p. 87–99.
- 2901 Lehman, P.W., Teh, S.J., Boyer, G.L., Nobriga, M.L., Bass, E., and Hogle, C., 2010, Initial impacts of
2902 *Microcystis aeruginosa* blooms on the aquatic food web in the San Francisco Estuary: *Hydrobiologia*,
2903 v. 637, p. 229–248.
- 2904 Lindberg, J. C., G. Tigan, L. Ellison, T. Rettinghouse, M.M. Nagel and K.M. Fisch. 2013. Aquaculture
2905 methods for a genetically managed population of endangered delta smelt. *North American Journal of*
2906 *Aquaculture* 75:2, 186-196; <http://dx.doi.org/10.1080/15222055.2012.751942>

- 2907 Loboschefskey, E., G. Benigno, T. Sommer, K. Rose, T. Ginn, and A. Massoudieh. 2012. Individual-level
2908 and population-level historical prey demand of San Francisco Estuary striped bass using a
2909 bioenergetics model. *San Francisco Estuary and Watershed Science*, 10(1). Retrieved from:
2910 <http://escholarship.org/uc/item/1c788451>
- 2911 Lopez, C.B., Cloern, J.E., Schraga, T.S., Little, A.J., Lucas, L.V., Thompson, J.K., and Burau, J.R.,
2912 2006, Ecological values of shallow-water habitats: Implications for restoration of disturbed
2913 ecosystems: *Ecosystems*, v. 9, p. 422–440.
- 2914 Lott, J. 1998. Feeding habits of juvenile and adult delta smelt from the Sacramento-San Joaquin River
2915 Estuary. *IEP Newsletter* 11(1):14–19.
- 2916 Lotze, H.K., Lenihan, H.S., Bourque, B.J., Bradbury, R.H., Cooke, R.G., Kay, M.C., Kidwell, S. M.,
2917 Kirby, M.X., Peterson, C.H., Jackson, J.B.C., 2006, Depletion, degradation, and recovery potential of
2918 estuaries and coastal seas: *Science*, v. 312 p. 1806–1809.
- 2919 Lucas, L.V., and Thompson, J.K., 2012, Changing restoration rules: Exotic bivalves interact with
2920 residence time and depth to control phytoplankton productivity: *Ecosphere*: v. 3, no. 12, p. 117,
2921 available at <http://dx.doi.org/10.1890/ES12-00251.1>
- 2922 Lucas, L.V., Cloern, J.E., Thompson, J.K., and Monsen, N.E., 2002, Functional variability of habitats
2923 within the Sacramento-San Joaquin Delta: Restoration implications: *Ecological Applications*, v. 12, p.
2924 1528–1547.
- 2925 Lucas, L.V., J.R. Koseff, S.G. Monismith, and J.K. Thompson. 2009a. Shallow water processes govern
2926 system-wide phytoplankton bloom dynamics - A modeling study. *Journal of Marine Systems* 75:70–
2927 86.
- 2928 Lucas, L.V., J.K. Thompson, and L.R. Brown. 2009b. Why are diverse relationships observed between
2929 phytoplankton biomass and transport time? *Limnology and Oceanography* 54:381–390.

- 2930 MacWilliams, M. Land E.S. 2013. Hydrodynamic simulation of circulation and residence time in
2931 Clifton Court Forebay. San Francisco Estuary and Watershed Science 11(2). jmie_sfews_11167.
2932 Retrieved from: <http://www.escholarship.org/uc/item/4q82g2bz>
- 2933 Mager, R. C., S. I. Doroshov, J. P. Van Eenennaam, and R. L. Brown. 2004. Early life stages of delta
2934 smelt. American Fisheries Society Symposium 39: 169-180.
- 2935 Mac Nally, R., Thompson, J.R., Kimmerer, W.J., Feyrer, F., Newman, K.B., Sih, A., Bennett, W.A.,
2936 Brown, L., Fleishman, E., Culberson, S.D., Castillo, G., 2010, An analysis of pelagic species decline
2937 in the upper San Francisco Estuary using multivariate autoregressive modeling (MAR): Ecological
2938 Applications, v. 20, p. 1417–1430.
- 2939 MacWilliams, M.L., and E.S. Gross. 2013. Hydrodynamic simulation of circulation and residence time
2940 in Clifton Court Forebay. San Francisco Estuary and Watershed Science, 11(2). Available at:
2941 <http://www.escholarship.org/uc/item/4q82g2bz>
- 2942 Manly, B.J.F. and Chotkowski, M.A., 2006, Two new methods for regime change analysis: Archiv für
2943 Hydrobiologie, v. 167, p. 593–607.
- 2944 Marine, KR, Cech, JJ, Jr. 2004. Effects of high water temperature on growth, smoltification, and
2945 predator avoidance in juvenile Sacramento River Chinook salmon. North American Journal of
2946 Fisheries Management 24:198-210.
- 2947 Martin, K.L.M. and D.L. Swiderski. 2001. Beach spawning in fishes: phylogenetic test of hypotheses.
2948 American Zoology 41:526-537.
- 2949 Massoudieh A., E. Loboschfsky, T. Sommer, T. Ginn, K. Rose, F. J. Loge (2011), Spatio-Temporal
2950 modeling of Striped- Bass egg and larvae movement and fate in Sacramento River Delta, Ecological
2951 Modeling, 222(19), 3513-3523

- 2952 Maunder, M.N., and Deriso, R.B., 2011, A state–space multistage life cycle model to evaluate
2953 population impacts in the presence of density dependence: illustrated with application to delta smelt
2954 (*Hypomesus transpacificus*): Canadian Journal of Fisheries and Aquatic Sciences, v. 68, p.1285–
2955 1306.
- 2956 Meng, L. and J.J. Orsi. 1991. Selective predation by larval striped bass on native and introduced
2957 copepods. Transactions of the American Fisheries Society 120:187–192.
- 2958 Merz, J. E. 2001. Diet of juvenile fall-run Chinook salmon in the lower Mokelumne River, California.
2959 California Fish and Game 87(3):102-114.
- 2960 Merz, J. E. 2002. Seasonal feeding habits, growth, and movement of steelhead trout in the lower
2961 Mokelumne River, California. California Fish and Game 88(3):95-111.
- 2962 Merz, J.E., Hamilton, S., Bergman, P.S., and Cavallo, B., 2011, Spatial perspective for delta smelt: a
2963 summary of contemporary survey data: California Fish and Game, v. 97, no. 4, p. 164–189.
- 2964 Miller, W.J. 2011. Revisiting assumptions that underlie estimates of proportional entrainment of delta
2965 smelt by State and Federal water diversions from the Sacramento-San Joaquin Delta. San Francisco
2966 Estuary and Watershed Science, 9(1). Available at: <http://escholarship.ucop.edu/uc/item/5941x1h8>
- 2967 Miller, W.J., Manly, B.F.J., Murphy, D.D., Fullerton, D., and Ramey, R.R., 2012, An investigation of
2968 factors affecting the decline of delta smelt (*Hypomesus transpacificus*) in the Sacramento-San Joaquin
2969 Estuary: Reviews in Fisheries Science, v. 20, p. 1–19.
- 2970 Miner, J. G., and R. A. Stein. 1996. Detection of predators and habitat choice by small bluegills: effects
2971 of turbidity and alternative prey. Transactions of the American Fisheries Society 125:97-103.
- 2972 Monismith, S.G., J.L. Hensch, D.A. Fong, N.J. Nidzieko, W.E. Fleenor, L.P. Doyle, and S.G. Schladow.
2973 2009. Thermal variability in a tidal river. Estuaries and Coasts 32: 100–110.

- 2974 Monsen, N. E., J. E. Cloern, and J. R. Burau. 2007. Effects of flow diversions on water and habitat
2975 quality: examples from California's highly manipulated Sacramento-San Joaquin Delta. San Francisco
2976 Estuary and Watershed Science 5(3):16 pages.
- 2977 Morgan, T.L., and D.H. Schoellhamer. 2013. Suspended-sediment flux and retention in a backwater
2978 tidal slough complex near the landward boundary of an estuary. Estuaries and Coasts 36: 300-318.
- 2979 Morinaka J. In Press. Acute mortality and injury of delta smelt associated with collection, handling,
2980 transport, and release at State Water Project fish salvage facility. Technical Report. Interagency
2981 Ecological Program of the Sacramento-San Joaquin Estuary, Sacramento, California.
2982
- 2983 Morinaka J. In press. A history of the operational and structural changes to the John E. Skinner Delta
2984 Fish Protective Facility from 1968 to 2010. Technical Report. Interagency Ecological Program of the
2985 Sacramento-San Joaquin Estuary, Sacramento, CA.
- 2986 Morris, T. In press. *Microcystis aeruginosa* status and trends during the Summer Townet Survey. IEP
2987 Newsletter Fall-Winter 2012-2013.
- 2988 Moulton, L. L. 1974. Abundance, growth, and spawning of the longfin smelt in Lake Washington.
2989 Transactions of the American Fisheries Society 103:46–52.
- 2990 Moyle, P.B., 2002, Inland fishes of California, 2nd edition: University of California Press, Berkeley, CA.
- 2991 Moyle, P.B., and Bennett, W.A., 2008, The future of the Delta ecosystem and its fish, Technical
2992 Appendix D, in Lund, J., Hanak, E., Fleenor, W., Bennett, W., Howitt, R., Mount, J., and Moyle, P.,
2993 eds., Comparing Futures for the Sacramento-San Joaquin Delta: Public Policy Institute of California,
2994 San Francisco, California.

- 2995 Moyle, P.B., Herbold, B., Stevens, D.E., and Miller L.W., 1992, Life history and status of delta smelt in
2996 the Sacramento-San Joaquin Estuary, California: Transactions of the American Fisheries Society, v.
2997 121, p. 67–77.
- 2998 Mueller-Solger, A.B., A.D.Jassby, and D.C. Mueller-Navarra. 2002. Nutritional quality of food
2999 resources for zooplankton (*Daphnia*) in a tidal freshwater system (Sacramento-San Joaquin River
3000 Delta), Limnology and Oceanography 47:1468–1476.
- 3001 Mueller-Solger, A.B., C.J. Hall, A.D. Jassby, and C.R. Goldman. 2006. Food resources for zooplankton
3002 in the Sacramento-San Joaquin Delta. Final Report to the Calfed Ecosystem Restoration Program,
3003 May 2006.
- 3004 Murawski, S. A., G.R. Clayton, R.J. Reed, and C.F. Cole. 1980. Movements of spawning rainbow
3005 smelt, *Osmerus mordax*, in a Massachusetts estuary. Estuaries 3:308-314.
- 3006 Murrell, M.C. and J.T. Hollibaugh. 1998. Microzooplankton grazing in northern San Francisco Bay
3007 measured by the dilution method. Aquatic Microbial Ecology 15:53–63.
- 3008 Myers R.A., N.J. Barrowman, J.A. Hutchings, and A.A. Rosenberg. 1995. Population dynamics of
3009 exploited fish stocks at low population levels. Science 269: 1106-1108.
- 3010 Newman, KB. 2008. Sample design-based methodology for estimating delta smelt abundance. San
3011 Francisco Estuary and Watershed Science 6: <http://repositories.cdlib.org/jmie/sfews/vol6/iss3/art3>.
- 3012 Nichols, F. H., J. E. Cloern, S. N. Luoma, and D. H. Peterson (1986), The modification of an estuary,
3013 *Science*, 231(4738), 567-573.
- 3014 Nichols, F.H., J.K. Thompson, and L.E. Schemel. 1990. Remarkable invasion of San Francisco Bay
3015 (California, USA) by the Asian clam *Potamocorbula amurensis*. II. Displacement of a former
3016 community. Marine Ecology Progress Series 66:95–101.

- 3017 Nobriga, M. 2002. Larval delta smelt composition and feeding incidence: environmental and
3018 ontogenetic influences. *California Fish and Game* 88:149–164.
- 3019 Nobriga, M. and F. Feyrer. 2007. Shallow-water piscivore-prey dynamics in the Sacramento-San
3020 Joaquin Delta. *San Francisco Estuary and Watershed Science* Vol. 5, Issue 2, Article 4.
- 3021 Nobriga, M., Feyrer, F., Baxter, R., and Chotkowski, M., 2005, Fish community ecology in an altered
3022 river delta: spatial patterns in species composition, life history strategies, and biomass: *Estuaries*, v.
3023 28, p. 776–785.
- 3024 Nobriga, M.L., E. Loboschfsky, F. Feyrer. In press. Common predator, rare prey: exploring juvenile
3025 striped bass predation on delta smelt in California's San Francisco Estuary. *Transactions of the*
3026 *American Fisheries Society*.
- 3027 Nobriga, M.L., Sommer, T.R., Feyrer, F., Fleming, K., 2008, Long-term trends in summertime habitat
3028 suitability for delta smelt, *Hypomesus transpacificus*: *San Francisco Estuary and Watershed Science*,
3029 v. 6, no. 1, available at <http://escholarship.org/uc/item/5xd3q8tx>.
- 3030 Paradis, A. R., P. Pepin, and J. A. Brown. 1996. Vulnerability of fish eggs and larvae to predation:
3031 review of the influence of the relative size of prey and predator. *Canadian Journal Fisheries and*
3032 *Aquatic Sciences* 53:1226-1235.
- 3033 NMFS (National Marine Fisheries Service). 2009. Biological opinion and conference opinion on the
3034 long-term operations of the Central Valley Project and State Water Project. National Marine Fisheries
3035 Service, Southwest Region, Long Beach, CA.
- 3036 NRC (National Research Council), 2012, Sustainable water and environmental management in the
3037 California Bay-Delta: National Research Council, The National Academies Press, Washington, DC.
- 3038 Ogden JC, Davis SM, Jacobs KJ, Barnes T, Fling HE., 2005, The use of conceptual ecological models
3039 to guide ecosystem restoration in South Florida. *Wetlands* 25(4):279–809.

- Orsi, J.J. and W.L. Mecum. 1996. Food limitation as the probable cause of a long-term decline in the abundance of *Neomysis mercedis* the opossum shrimp in the Sacramento-San Joaquin estuary. Pages 375–401 in J.T. Hollibaugh, editor. San Francisco Bay: the ecosystem. American Association for the Advancement of Science. San Francisco, CA.
- Parker, A.E., R.C. Dugdale, and F. P. Wilkerson. 2012. Elevated ammonium concentrations from wastewater discharge depress primary productivity in the Sacramento River and the Northern San Francisco Estuary. *Marine Pollution Bulletin* 64:574–586.
- Quist, MC, Hubert, WA, Rahel, FJ. 2004. Relations among habitat characteristics, exotic species, and turbid-river cyprinids in the Missouri River drainage of Wyoming. *Transactions of the American Fisheries Society* 133:727-742.
- Reclamation, 2011, Adaptive management of fall outflow for delta smelt protection and water supply reliability: U.S. Bureau of Reclamation, Sacramento, CA, available at <http://www.usbr.gov/mp/BayDeltaOffice/docs/Adaptive%20Management%20of%20Fall%20Outflow%20for%20Delta%20Smelt%20Protection%20and%20Water%20Supply%20Reliability.pdf>
- Reclamation, 2012, Adaptive management of fall outflow for delta smelt protection and water supply reliability: U.S. Bureau of Reclamation, Sacramento, CA, available at http://deltacouncil.ca.gov/sites/default/files/documents/files/Revised_Fall_X2_Adaptive_MgmtPlan_EVN_06_29_2012_final.pdf.
- Rodriguez, M. A. and Lewis, W. M. 1997. Structure of fish assemblages along environmental gradients in floodplain lakes of the Orinoco River. *Ecological Monographs* 67: 109-128.
- Rollwagen-Bollens, G.C. and D.L. Penry. 2003. Feeding dynamics of *Acartia* spp. copepods in a large, temperate estuary (San Francisco Bay, CA). *Marine Ecology Progress Series* 257:139–158.

- Rose, K.A., J.H. Cowan, K.O. Winemiller, R.A. Myers, and R. Hilborn. 2001. Compensatory density-dependence in fish populations: importance, controversy, understanding, and prognosis. *Fish and Fisheries* 2: 293-327.
- Rose, K., J. Anderson, M. McClure, G. Ruggerone. 2011. Salmonid Integrated Life Cycle Models Workshop Report of the Independent Workshop Panel, Workshop Organized by the Delta Science Program. Available at http://deltacouncil.ca.gov/sites/default/files/documents/files/Salmonid_ILCM_workshop_final_report.pdf.
- Ruhl, C.A., and Schoellhamer, D.H., 2004, Spatial and Temporal Variability of Suspended-Sediment Concentrations in a Shallow Estuarine Environment: San Francisco Estuary and Watershed Science. v. 2, no. 2, available at <http://escholarship.org/uc/item/1g1756dw>
- Schoellhamer, D.H., 2001, Influence of salinity, bottom topography, and tides on locations of estuarine turbidity maxima in northern San Francisco Bay, in McAnally, W.H. and Mehta, A.J., ed., Coastal and Estuarine Fine Sediment Transport Processes: Elsevier Science B.V., p. 343-357, available at <http://ca.water.usgs.gov/abstract/sfbay/elsevier0102.pdf>.
- Schoellhamer, D.H., 2011, Sudden clearing of estuarine waters upon crossing the threshold from transport to supply regulation of sediment transport as an erodible sediment pool is depleted: San Francisco Bay, 1999: *Estuaries and Coasts*, v. 34, p. 885–899.
- Schoellhamer, D.H., Wright, S.A., and Drexler, J.Z., 2012, Conceptual model of sedimentation in the Sacramento – San Joaquin River Delta: *San Francisco Estuary and Watershed Science* 10(3). Available at: <http://www.escholarship.org/uc/item/2652z8sq>

- Scholz, N.L., E. Fleishman, L. Brown, I. Werner, M.L. Johnson, M.L. Brooks, C.L. Mitchelmore, and D. Schlenk. 2012. A perspective on modern pesticides, pelagic fish declines, and unknown ecological resilience in highly managed ecosystems. *Bioscience* 62:428-434.
- Shoji, J., E. W. North, and E.D. Houde. 2005. The feeding ecology of *Morone americana* larvae in the Chesapeake Bay estuarine turbidity maximum: the influence of physical conditions and prey concentrations. *Journal of Fish Biology* 66(5): 1328-1341.
- Sirois, P., and J. J. Dodson. 2000a. Influence of turbidity, food density and parasites on the ingestion and growth of larval rainbow smelt *Osmerus mordax* in an estuary turbidity maximum. *Marine Ecological Progress Series* 193:167-179.
- Sirois, P., and J. J. Dodson. 2000b. Critical periods and growth-dependent survival of larvae of an estuarine fish, the rainbow smelt *Osmerus mordax*. *Marine Ecological Progress Series* 203(233-245).
- Slater, S.B. and R.D. Baxter. In review. Investigation of feeding and potential food limitation in delta smelt, *Hypomesus Transpacificus*, in the upper San Francisco Estuary, California. *San Francisco Estuary and Watershed Science*.
- Sobczak, W.V., Cloern, J.E., Jassby, A.D., and Muller-Solger, A.B., 2002, Bioavailability of organic matter in a highly disturbed estuary: The role of detrital and algal resources: *Proceedings of the National Academy of Sciences*, v. 99, p. 8101–8105.
- Sobczak, W.V., J.E. Cloern, A.D. Jassby, B.E. Cole, T.S. Schraga, and A. Arnsberg. 2005. Detritus fuels ecosystem metabolism but not metazoan food webs in San Francisco estuary's freshwater Delta. *Estuaries* 28:124–137.
- Sogard, S. M. 1997. Size-selective mortality in the juvenile stage of teleost fishes: A review. *Bulletin of Marine Science* 60:1129–1157.

- 3105 Sommer, T., Armor, C., Baxter, R., Breuer, R., Brown, L., Chotkowski, M., Culberson, S., Feyrer, F.,
3106 Gingras, M., Herbold, B., Kimmerer, W., Mueller-Solger, A., Nobriga, M., and Souza, K., 2007, The
3107 collapse of pelagic fishes in the upper San Francisco Estuary: Fisheries, v. 32, no. 6, p. 270–277.
- 3108 Sommer, T., Mejia, F., Nobriga, M., Feyrer, F., and Grimaldo, L., 2011, The spawning migration of
3109 delta smelt in the upper San Francisco Estuary: San Francisco Estuary and Watershed Science, v. 9,
3110 no. 2, available at <http://www.escholarship.org/uc/item/86m0g5sz>.
- 3111 Sommer, T., and Mejia, F. 2013. A place to call home: a synthesis of delta smelt habitat in the upper
3112 San Francisco Estuary. San Francisco Estuary and Watershed Science June 11(2).Available at:
3113 <http://www.escholarship.org/uc/item/32c8t244>
- 3114 Stevens, D. L. 1963. Food habits of striped bass, *Roccus saxatilis* (Walbaum) in the Sacramento-Rio
3115 Vista area of the Sacramento River. University of California.
- 3116 Stevens, D.E. 1966. Food habits of striped bass, *Roccus saxatilis*, in the Sacramento-San Joaquin Delta.
3117 Pages 97–103 in J.T. Turner and D.W. Kelley, editors. Ecological studies of the Sacramento-San
3118 Joaquin Delta, part II, fishes of the delta. California Department of Fish and Game Fish Bulletin 136.
- 3119 Swanson, C., Reid, T., Young, P.S., and Cech, J.J., Jr. 2000. Comparative environmental tolerances of
3120 threatened delta smelt (*Hypomesus transpacificus*) and introduced wakasagi (*H. nipponensis*) in an
3121 altered California estuary: Oecologia, v. 123, p. 384–390.
- 3122 Sweetnam, D.A. 1999. Status of delta smelt in the Sacramento-San Joaquin Estuary. California Fish and
3123 Game 85:22–27.
- 3124 Thom R. 2000. Adaptive management of coastal ecosystem restoration projects. Ecological Engineering
3125 15:365–372.

- 3126 Thomson, J.R., Kimmerer, W.J., Brown, L.R., Newman, K.B., Mac Nally, R., Bennett, W.A., Feyrer,
3127 F., and Fleishman, E., 2010, Bayesian change-point analysis of abundance trends for pelagic fishes in
3128 the upper San Francisco Estuary: Ecological Applications, v. 20, p. 1431–1448.
- 3129 Touzeau, S., and G.L. Gouze 1998. On the stock-recruitment relationships in fish population models.
3130 Environmental Modeling and Assessment 3:87-93.
- 3131 Townend, I.H. 2004. Identifying change in estuaries. Journal of Coastal Conservation 10:5-12.
- 3132 Turner, J.L. and H.K. Chadwick. 1972. Distribution and abundance of young-of-the-year striped bass,
3133 *Morone saxatilis*, in relation to river flow in the Sacramento-San Joaquin Estuary. Transactions of the
3134 American Fisheries Society 101:442-452.
- 3135 USGS (U.S. Geological Survey), 2008, Tracking organic matter in Delta drinking water: Science
3136 Action: News from the CALFED Science Program, April 2008, CALFED Science Program
3137 Sacramento, CA.
- 3138 USFWS (United States Fish and Wildlife Service), 2008, Formal Endangered Species Act consultation
3139 on the proposed coordinated operations of the Central Valley Project (CVP) and State Water Project
3140 (SWP): U.S. Fish and Wildlife Service, Sacramento, CA.
- 3141 Wagner, R.W. 2012. Temperature and tidal dynamics in a branching estuarine system. PhD dissertation.
3142 Berkeley: University of California.
- 3143 Wagner, R.W., M. Stacey, L.R. Brown, and M. Dettinger. 2011. Statistical models of temperature in the
3144 Sacramento–San Joaquin Delta under climate-change scenarios and ecological implications. Estuaries
3145 and Coasts 34: 544–556.
- 3146 Walters, C.J., Juanes, F. 1993. Recruitment limitation as a consequence of natural selection for use of
3147 restricted feeding habitats and predation risk taking by juvenile fishes. Canadian Journal of Fisheries
3148 and Aquatic Sciences 50:2058-2070.

- 3149 Wang, J. C. S. 1986. Fishes of the Sacramento-San Joaquin Estuary and adjacent waters, California: A
3150 Guide to the early life histories. Interagency Ecological Study Program for the Sacramento-San
3151 Joaquin Estuary, Technical Report 9.
- 3152 Wang, J. C. S. 1991. Early life stages and early life history of the delta smelt, *Hypomesus*
3153 *transpacificus*, in the Sacramento-San Joaquin estuary with comparison of early life stages of the
3154 longfin smelt, *Spirinchus thaleichthys*. U.S. Army Corps of Engineers, Technical Report FS/BIO-
3155 IATR/91-28.
- 3156 Wang, J. C. S. 2007. Spawning, early life stages and early life histories of the Osmerids found in the
3157 Sacramento-San Joaquin Delta of California. U.S. Department of the Interior, Bureau of Reclamation,
3158 Mid-Pacific Region, Byron, California. Tracy Fish Facilities Studies, Volume 38, 72 pages plus
3159 appendices.
- 3160 Warner, J.C., Schoellhamer, D.H., Ruhl, C.A., and Burau, J.R., 2004, Floodtide pulses after low tides in
3161 shallow subembayments adjacent to deep channels: Estuarine, Coastal and Shelf Science, v. 60, no. 2,
3162 p. 213–228.
- 3163 Werner, I., L. Deanovic, D. Markiewicz, M. Stillway, N. Offer, R. Connon, and S. Brander. 2008.
3164 Pelagic Organism Decline (POD): Acute and chronic invertebrate and fish toxicity testing in the
3165 Sacramento-San Joaquin Delta 2006–2007. Final Report. U.C. Davis–Aquatic Toxicology
3166 Laboratory, Davis, California.
- 3167 Werner, I., L.A. Deanovic, D. Markiewicz, J. Khamphanh, C.K. Reece, M. Stillway, and C. Reece.
3168 2010a. Monitoring acute and chronic water column toxicity in the northern Sacramento-San Joaquin
3169 Estuary, California, USA, using the euryhaline amphipod, *Hyalella azteca*: 2006–2007.
3170 Environmental Toxicology and Chemistry 29: 2190–2199.

- 3171 Werner, I., D. Markiewicz, L. Deanovic, R. Connon, S. Beggel, S. Teh, M. Stillway, C. Reece. 2010b.
3172 Pelagic Organism Decline (POD): Acute and chronic invertebrate and fish toxicity testing in the
3173 Sacramento-San Joaquin Delta 2008–2010, Final Report. U.C. Davis–Aquatic Toxicology
3174 Laboratory, Davis, California.
- 3175 Weston, D.P., A.M. Asbell, S.A. Lesmeister, S.J. Teh, M.J. Lydy. 2012. Urban and agricultural
3176 pesticide inputs to a critical habitat for the threatened delta smelt (*Hypomesus transpacificus*). Final
3177 report to the POD Management Team of the Interagency Ecological Program for the San Francisco
3178 Estuary.
- 3179 Whipple, As, Grossinger, R.M., Rankin, D., Stanford, B., and Askevold, R., 2012, Sacramento-San
3180 Joaquin Delta Historical Ecology Investigation: Exploring Pattern and Process: San Francisco Estuary
3181 Institute, Richmond, CA.
- 3182 Whitfield, A.K. 1999. Ichthyofaunal assemblages in estuaries: A South African case study. Reviews in
3183 Fish Biology and Fisheries 9:151–186.
- 3184 Wilkerson F.P., R.C. Dugdale, V.E. Hogue, and A. Marchi. 2006. Phytoplankton blooms and nitrogen
3185 productivity in San Francisco Bay. Estuaries and Coasts 29:401–416.
- 3186 Winemiller, K. O. and K. A. Rose. 1992. Patterns of life-history diversification in North-American
3187 fishes implications for population regulation Canadian Journal of Fisheries and Aquatic Sciences
3188 49:2196-2218.
- 3189 Winder M, Jassby AD (2011) Shifts in zooplankton community structure: Implications for food-web
3190 processes in the upper San Francisco Estuary. Estuaries and Coasts. 34: 675-690
- 3191 Winder, M.A. Jassby and R. McNally. 2011. Synergies between climate anomalies and hydrological
3192 modifications facilitate estuarine biotic invasions. Ecology Letters. 14(8):749–757.

- 3193 Wright, SA, Schoellhamer, DH. 2004. Trends in the sediment yield of the Sacramento River, California,
3194 1957-2001. San Francisco Estuary and Watershed Science 2:
3195 <http://repositories.cdlib.org/jmie/sfews/vol2/iss2/art2>.
- 3196 York, J.K., B.A. Costas and G.B. McManus. 2010. Microzooplankton grazing in green water—results
3197 from two contrasting estuaries. Estuaries and Coasts 34:373-385.

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